Potentialities of the Urban Volume: Mapping underground resource potential and deciphering spatial economies and configurations of multi-level urban spaces

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PAR

Michael Robert DOYLE

acceptée sur proposition du jury:

Prof. D. Dietz, président du jury
Prof. Ph. Thalmann, Prof. A. Parriaux, directeurs de thèse
Dr V. Bühlmann, rapporteuse
Prof. A. Sevtsuk, rapporteur
Dr J. Chenal, rapporteur

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Abstract

This dissertation looks at the urban volume, in its natural and artificial materiality, as a source of potential for future urbanization. Underground resources—for buildable space, geomaterials, groundwater and geothermal energy—tend to be addressed only as needs arise. This has historically led to conflicts between uses: basements and tunnels flooded by rising aquifers; drinking water sources endangered by infrastructures that carry pollutants into groundwater systems. The work was carried out as part of the Deep City Project, which argues for a paradigm shift of 'resources to needs' in which the potential of underground resources is addressed prior to any urban project or plan. The work presented here further develops a methodology to map the combined potentials of resources and includes an original investigation of the spatial relationships between underground and surface urban commercial spaces.

The prologue introduces the overarching problematic and concepts using a dramatization of an incident that occurred during the construction of the M2 metro line in Lausanne in 2005. This concrete example sets the stage for the first chapter, where the theoretical framework of the dissertation is laid out in detail. The resources to needs paradigm is elaborated by looking at the underground as it has been addressed in normative city models, arguing that the dominant ecological and mechanical models do not provide the adequate framework for thinking resources prior to needs. This reflection draws on concepts from information and urban theory as well as philosophy, arguing for an approach to the mass of the urban volume as an economy of communication—of encounter and avoidance.

The second chapter specifically addresses underground space through a spatial configurational analysis of the Montreal downtown, where a network of indoor and outdoor commercial spaces comprises a unique spatial volume. Relationships between the spaces are calculated using multiple accessibility metrics on a 3D spatial network model built in GIS. Common configurational characteristics are extracted using principal component analysis and placed in a spatial econometric model, which looks at the influence of spatial configuration on rental value per square meter of food and retail spaces. The results suggest that certain accessibility metrics contribute more than others to this value, but a subsequent geographically weighted regression reveals that this impact is varied in space and does not establish a clear separation between indoor and outdoor spaces.

The third chapter presents the application of the Deep City mapping method to three case study cities—San Antonio, Texas, Hong Kong, China, and Dakar, Senegal—which have relatively diverse and complex relationships to their geology and surface urbanization. In each case, adjustments are made to the methodology, particularly in how the potential of the surface urban form contributes to the underground potential of the city. The results of the maps, which provide a city-wide overview of underground potential, are discussed by returning to some of the projects and problematics currently addressed by each city's urban planning departments or master plans. The conclusion summarizes the research as a whole and revisits the theoretical framework in discussing future avenues for research and practical application.

Keywords: urban morphology, GIS, urban diagnostic tool, Dakar, San Antonio, Hong Kong, Montreal, spatial econometrics, analytic hierarchy process, spatial network analysis

Résumé

Ce travail de thèse porte sur le volume urbain, en tant que masse naturelle et artificielle, comme une source de potentiel pour l'urbanisation future. Les ressources souterraines—l'espace constructible, les géomatériaux, les eaux souterraines et l'énergie géothermique—sont trop souvent abordées trop tard dans la planification quand les besoins des projets ont déjà été définis. Cela mène à des conflits entre usages: inondation des sous-sols dû à l'augmentation du niveau de l'aquifère; pollution d'une source souterraine d'eau potable par un système géothermique. Ce travail a été mené dans le cadre du projet Deep City, qui vise une approche des 'ressources aux besoins'. Ce paradigme alternatif promeut l'intégration des ressources souterraines en amont du montage des projets urbains et des plans directeurs. Le travail présenté ici avance une méthodologie pour cartographier les potentiels combinés des ressources et conduit une étude originale des relations spatiales entre les espaces commerciaux en surface et en sous-sol.

La préface (*prologue*) présente la problématique et les concepts à travers un incident qui a eu lieu à Lausanne lors de la construction du métro M2 en 2005. Ce cas concret sert de point de départ pour le premier chapitre, qui élabore le cadre théorique de la thèse. Le paradigme de 'ressources aux besoins' est élaboré en étudiant la manière dont le sous-sol est conçu dans les modèles normatifs de la ville, ce qui mène au constat que les approches mécanistes et écologiques qui prédominent encore aujourd'hui ne fournissent pas de cadre adéquat pour penser aux ressources en amont des besoins. Cette réflexion s'appuie sur la théorie de l'information, la théorie urbaine et la philosophie et propose une approche qui aborde la masse du volume urbain comme une économie de la communication—de rencontre et d'évitement.

Le deuxième chapitre s'interroge sur l'espace souterrain par une analyse de la configuration spatiale du centre-ville de Montréal, où un réseau d'espaces intérieurs et extérieurs en sous-sol et en surface constitue un volume spatial unique. Les relations entre les espaces commerciaux de détail et de restauration sont calculées avec plusieurs mesures d'accessibilité sur un modèle de réseau tridimensionnel monté en SIG. Les caractéristiques spatiales communes sont identifiées avec une analyse par composantes principales et prises comme variables indépendantes dans un modèle économétrique spatial qui tente d'identifier l'impact de la configuration sur le prix du loyer au mètre carré. Les résultats suggèrent que certaines mesures d'accessibilité contribuent plus que d'autres à expliquer la distribution de cette valeur, mais une deuxième régression pondérée géographiquement révèle que cet impact est spatialement hétérogène et n'établit pas une séparation claire et nette entre les espaces extérieurs et intérieurs.

Le troisième chapitre présente l'application de la méthode Deep City de la cartographie du potentiel des ressources souterraines à trois villes—San Antonio, au Texas, Dakar au Sénégal et Hong Kong en Chine—qui ont chacune une relation complexe avec leur géologie et l'urbanisation en surface. Pour chaque ville, la méthode s'adapte aux conditions géologiques et en particulier aux données disponibles pour évaluer la contribution de la morphologie urbaine au potentiel de ressources souterraines. Les résultats de la cartographie, qui présente une appréciation du potentiel souterrain à l'échelle territoriale, sont discutés en retournant à des projets élaborés ou à des problématiques identifiées par les processus récents de planification. La conclusion revient sur la recherche et s'appuie à nouveau sur le cadre théorique pour lancer des pistes de réflexion pour de futures recherches et l'opérationnalisation des résultats.

Mots clés : morphologie urbaine, SIG, outil de diagnostic urbain, Dakar, San Antonio, Hong Kong, Montréal, économétrie spatiale, analyse hiérarchique des procédés, analyse spatiale

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Prologue

Rhythms Interrupted

Lausanne. Tuesday, February 22, 2005. 6 p.m. Dinner at a fast food restaurant is interrupted by a man in hard hat, boots covered in mud, out of breath. Ovens switched off. Half-prepared burgers left on the counter. At a shopping market next door, the filling of grocery carts and baskets is interrupted by a hurried announcement inviting customers to come immediately to the registers.

The mundane on hold. Everyone out.

Minutes earlier the work of a header machine boring without problem through molasse and moraine beneath the Place Saint-Laurent is interrupted by a sudden and unexpected flow of water-laden clay loam and gravel sands—remains of a glacial lake itself interrupted long ago by progressive peat infill and later sealed off beneath the public square. The tunnel gradually fills with mud and a cavity begins to form. The pavement—whose stability no passerby would have questioned several minutes earlier—is now only a 30-centimeter crust spanning a cavern estimated to be nearly 1000 cubic meters. The following twenty-one days are a fight to return to stability. The river of mud is contained. Building foundations and façades are reinforced. Construction workers are fed and warmed in the bitter cold of winter. The worries of local residents are assuaged. Several weeks later the ordeal is over. On the 18th of June in front of the Saint-Laurent church, the rhythms of a concert band celebrate a return to the rhythms of everyday life. The tunnel work can continue. The flows of the glacial lake have once again been silenced.[1]

The glacial lake is a forgotten mass. It was an interruption, noise on a channel. It was born of a chance turn of events. The departure of glaciers millions of years ago left a depression in

[1] Luc Jaccard and Maurice Schobinger, *M2: le défi* (Lausanne: Editions Favre, 2008); Robin Marchant, "L'effondrement de St-Laurent," Communiqué de presse (Lausanne, no date), https://www.unil.ch/mcg/fr/home/menuinst/pour-les-medias/effondrement-de-st-laurent.html.

which water collected, interrupted from its descent in the Lake of Geneva by a natural dam of impervious moraine.[2] It is a stock of time. Pollen grains suggest that, 12,000 years ago, the boggy lake was surrounded by birch and willow trees. Evidence of human settlement suggests that the lake was also a place over 6,000 years ago where passages were interrupted, where one day trees were cleared and wheat was planted. This archive is interrupted by today's building foundations, but at some point the glacial lake was no longer a reservoir of value. Situated on one of the important paths in Lausanne leading from Rome to Paris, it was paved over.[3]

The glacial lake was no longer a place where people wanted to encounter its boggy ground. By the 10th century, on solid ground nearby, a church was built, marking a spot connecting the mundane to the divine. Marking a place to stop.[4] A new kind of encounter. The street outside was not just a place of passage, channeling people from the Place de la Palud out the gates of the city towards France. That channel also sorted encounters. Peddlers, eventually shopkeepers, sold their wares. In some places more people passed—those were strategic places. Goods sold, services offered, quasi-objects for turning the traveler, quasi-subject, momentarily into a potential client. Other corners along the street were better for getting away from the crowd. Avoiding the noise, creating a calm. From passerby to patron.

The glacial lake is marked by chains of substitution—ice, water, swamp, loam, foundation for the street—and as a mass has participated in other reconfigurations, as an informational motor. Its encounter with the header machine had the potential on that day in February to reconfigure the relationship between people, between the molasse and moraine and a mass of clay and loam, the continued possibility of passage. Yes, it could have been disastrous. That is the nature of its potentiality. We know from its own archive, that its potential has been actualized in different ways over time. Could it be any other way? Or do we continue to put the mass back in its place where we think it should be? We think we know the city because we've addressed it in so many ways. We've covered it in language and forgotten that the material is already the integral. Of all language—the *logos*. It is the mark of passage, of traces—of the *graphein*.

[2] Marc Weidmann, *Les dessous d'une ville: Petite géologie lausannoise*, Les cahiers de la forêt lausannoise 2 (Lausanne: Direction des finances de la ville de Lausanne. Service des forêts, domaines et vignobles, 1987).

[3] Louis Polla, *De Saint Etienne Au Général Guisan: Louis Polla Raconte La Vie de Cent Personnages Qui Ont Donné Leur Nom Aux Rues de Lausanne* (Lausanne: Editions 24 heures, 1981).

[4] Jean Charles Biaudet, ed., *Histoire de Lausanne*, Univers de La France et Des Pays Francophones (Lausanne: Payot, 1982).

Figure 0.1. View from above of the hole left where Place St-Laurent collapsed during the construction of the M2 metro line (soucre: Schöbinger & Jaccard 2008).

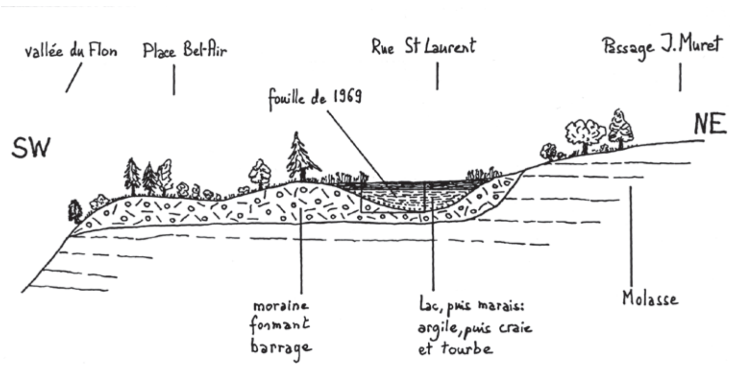


Figure 0.2. A schema of the glacial lake situated beneath present-day Rue St-Laurent before human settlement (source: Weidmann, 1987, p. 29).

"La ville fait du bruit, mais le bruit fait la ville"

- Serres, Le parasite (1980)

"The town makes the noise, but the noise makes the town"

- Serres, The Parasite (1982)

Chapter 1

Resources to Needs

Constituting Reservoirs of Potentiality

What is the urban underground? 'Ground' (from Old English *grund*) implies not only 'surface of the earth' but also 'bottom', the lowest depth. By going beneath it, a limit is crossed, between surface and subsurface. Throughout history and in different cultures, this limit has been conceived not only literally but also symbolically with death and with descent and rebirth.[1] The word 'urban' as an adjective means 'of the city' (from Latin *urbanus*) and in Roman times was the place of humanity in separation from the outside world (the *orbis*). This 'outside' was not necessarily geographic, but referred to the global or the universal—that which connected the locality of the *urbs*.[2,3] The Roman Empire itself was such a network, founded on stasis and flux, on roads and ongoing foundations of political and social orders.[4] The 'ground' was locally integrated with this network, a source not only of materials but also, as at the Phlegraean Fields near Naples, a mass out of which have been carved places of movement and protection.[5] The urban underground is not outside or apart from the city but comprises local articulations of mass.

The contemporary scientific literature increasingly recognizes this volumetric or vertical stratification of the urban and its expansion downwards. The fact that 'urban' appears more and more in noun form ('the urban') stems perhaps not only from the fact that urban processes are recognized as 'planetary',[6] but that the *urbs* and *orbis* are no longer thought of as being nested—they are mutually

1 Rosalind H Williams, *Notes on the Underground an Essay on Technology, Society, and the Imagination* (Cambridge, Mass.: MIT Press, 2008), http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=230708.

2 *Orbis* refers literally to the globe (etymonline.com)

3 Marcel Hénaff, *La ville qui vient*, Kindle Edition (without page numbers) (Paris: l'Herne, 2008).

4 Michel Serres, *Rome: The First Book of Foundations*, orig. 1974 (1983; repr., London: Bloomsbury Academic an imprint of Bloomsbury Publishing Plc, 2015).

5 Luca Ortelli, "Le souterrain au quotidien," in *Vingt mille lieux sous les terres : espaces publics souterrains*, ed. Pierre von Meiss and Florinel Radu (Lausanne: Presses Polytechniques Universitaires Romandes, 2004), 43–58.

6 Neil Brenner and Christian Schmid, "Towards a New Epistemology of the Urban?," *City* 19, no. 2–3 (May 4, 2015): 151–82.

implicated in a sort of common economy.[7] Much of the literature on the underground makes normative statements about this economy (*oikonomia*) of the urban volume, about the laws (*nomos*) that govern (or should govern) the urban volumes of the world (*oikos*). Other researchers focus on the architectonics (*architekton*) of the urban volume, with some investigating its local laws (the *arkhe*) with others, particularly architects and designers, taking these laws as given and developing the different ways they can be articulated (the *tekton*). They all share the call for this mass to constitute a new 'here', a place whose traces (the *graphein*) have been neglected or over-determined, multiplied into language (the *logos*).[8]

This chapter will explore these ideas and present in greater depth the figures that first emerged in the prologue. If the prologue sought to dramatize these figures in a specific case, the following pages will unfold and unpack them within a larger philosophical framework. The glacial lake lying beneath the St-Laurent Street is a geological motor. On the one hand it transports in geological time the water that continues to seep from the pores in the ground above. On the other, it transforms, processing, irreversibly, sand, silt, clay, plantings, vegetation, which it transformed over millennia into the boggy loam that was met with surprise by inhabitants in the 19th, 20th and 21st centuries. It is not only a stock and a reservoir of water and minerals but also of information—in a language of its own, but translated, for example, by geologists and archeologists. As a reservoir, it is of course only a subset, first of the earth, and then of the ultimate capital, the sun.[9] It is a moment of bifurcation in a stream upon which multiple motors act, from the extraction of water in Neolithic times for drinking or irrigation to the construction above it and around it today for containment. It has been mapped, designated, but somehow it is regularly forgotten only to be rudely rediscovered.

The street also transports and transforms. It is part of a larger motor, that of the city. The street channels movements, articulates a local bifurcation and deviation. The Rue St-Laurent in the 17th century directed movement from an important public square, the Place de la Palud, out of the city through the city gates onto the road heading westward towards France. Just as it transports, the motor of the street transforms the open field, the any-path, to the single path, the channel. Of course, the street is not only a place of movement, but also of rest—it stocks and becomes itself a reservoir. The stream of passersby is interrupted. Whether the interruption came first or the activities, local reservoirs, is of no importance. The anonymous traveler becomes subject, coded by the informational motor. Stop, stay a while. Come into my shop. Be my guest. Take this in exchange for something—buyers and sellers. Leave without

7 Hénaff, *La ville qui vient*.

8 Michel Serres, *Statues: The Second Book of Foundations*, trans. Randolph Burks, Kindle edition (1987; repr., London: Bloomsbury, 2015).

9 Michel Serres, *The Parasite*, trans. Lawrence R. Schehr (1980; repr., Baltimore: Johns Hopkins University Press, 1982).

paying—thief. And so on. This motor operates not only on the mass of the crowd, but also on the ground and deeper. Stone is extracted and cut, stacked, transformed to better bind the stacking, given inscriptions, sculpted. It is informed through these processes and then coded, named, described—quarried stone, paving, brick, mortar, headstone of the beloved, statue of the revered. From the anonymous marks of the *graphein*, it enters a *logos*. Geology has its own names for all of this: molasse, moraine, sand, silt.

'Motor' is not employed here as a metaphor, but as a way of deciphering the mechanisms that are common to the urban volume. This common motor is an abstract machine, which first chooses or draws from the mass and then gives it stability and order. Deleuze and Guattari illustrate this double articulation with the process by which sandstone and schist are sorted and laid down (first articulation) and then gradually layered into flysch (second articulation).[10] Such a motor (or set of motors) is not unique to geology, but is "a special case of a more general class of structures, stratified systems, to which not only human bureaucracies and biological species belong, but also sedimentary rock."[11] Even if, however, there is a common motor or system of motors, the double articulation is not a process of unambiguous laying down, or writing, but rather of folding and encoding. The community comes from a crowd that one day shared something that bound them (community derives from *communas*, or that which is shared). The genealogy of this binding is encoded in the community itself, like the processes that bind sandstone and schist. Understanding these processes is less about reading or playing back than deciphering from various (disciplinary) angles: "the best model [remains] the thing itself."[12]

1.2 Motors and models: transport and transformation in urban models

Michel Serres identifies three types of motors. The first and the second are vectorial and transformational.[13] The vectorial motor is the machine, a transfer of forces. It transports. Its central concern is movement, a movement in a reversible time. From home to work, to the grocery, back home—eternal return. It is epistemic, viewed from a single point. The second motor was born with the thermodynamics of Carnot, from a difference in temperature comes a change in state. It is an apparatus, a system. It is no longer about the movement of single elements, but the flow of the mass. From difference comes transformation. The cold crowd rushes. The ground is warmer there than here. Or a foundation is being laid—a place born where there was none before. Maybe the crowd is going to protest. The land to clear will cut down a forest; the industry will pollute the river, the air

[10] Gilles Deleuze and Félix Guattari, *Mille Plateaux*, Collection "Critique," t. 2 (Paris: Éditions de minuit, 1980).

[11] Manuel De Landa, *A Thousand Years of Nonlinear History*, Swerve Editions (New York: Zone Books, 1997), 62.

[12] Michel Serres, *The Birth of Physics* (1977; repr., Manchester: Clinamen Press, 2000), 163.

[13] Michel Serres, *La Distribution*, Hermès 4 (Paris: Editions de Minuit, 1977).

or the groundwater. There will be no going back. Transformational motors operate in an irreversible time. From two points, then and now: diastemic.

Each motor needs a reservoir, which precedes the cycle and the circulation. It is the beginning of the chain, the *arkhe*. It is an invariance. In the 1970s, the biologist Jacques Monod concluded by looking at cellular reproduction that this invariance preceded teleology (the drive towards an end state).[14] There is no project but only birth, reproduction and the work necessary to avoid the dissolution of the system or organism. Teleology is animated only by this fight against a lasting, irreversible (thermodynamic) death. For Serres, this reservoir is the *ichnography*, void of project like the footprints in the sand that trace back to a point of origin that has been partially erased by time and tides.[15] The different motors that draw from the ichnography generate *scenographies*, particular viewpoints (*episteme*). The ichnography is then "all scenography, every profile, every appearance."[16] If ichnography is noise, scenography is music; if the former is paint, the latter is a scene emerging from a distribution of colors. The tension between ichnography and scenography is synonymous to the one between the footprints left in the sand (the material trace or *graphein*) and the attempts to tell their story in language (*logos*).[17] A tension between geography and geology, sociology, anthropology, and so on, as different scenographies of the motoric operations of the earth and of its inhabitants.

Urban theories of city form tend to reflect a particular model or scenography. Drawing on a history of normative models and theories, from Sebastiano Serlio to Kevin Lynch and Spiro Kostof, urbanist David Grahame Shane identifies three recurring models: the city of faith, the city as a machine and the ecological city.[18] The city of faith organizes its form around a ceremonial center. Its geometry draws on the divine as source of meaning and direction on earth. Its motor mediates and transports the values or norms considered valuable by the particular society. The divine constitutes a reservoir from which a cosmological scenography is drawn by a unidirectional motor. Even if the city of faith is still very present in evolving notions of the divine,[19] the city as a machine remains the dominant normative model of our era. Where the city of faith is centered on stability, the city as a machine is a system of flows to

[14] Jacques Monod, *Chance and Necessity; an Essay on the Natural Philosophy of Modern Biology* (1971; repr., New York: Vintage Books, 1972).

[15] The word ichnography (*ichnographia*) is composed of the Greek for footprint (*ichnos*) and trace (*graphein*), see Michel Serres, *Genèse* (Paris: B. Grasset, 1982).

[16] Michel Serres, "Noise," trans. Schehr Lawrence R., *SubStance*, Issue 40: Determinism, 12, no. 2 (1983): 58.

[17] In his reading of the roman poet Lucretius's *De Rerum Natura* (On the Nature of Things), Serres argues that from the point of view of an atomist physics the ichnography is the chaos cloud with no direction (in French *sens*) or meaning (also *sens* in French, an important double meaning for Serres). This is how scenography can be linked back to the material world and not limited to a logos of human origin, see Serres, *The Birth of Physics*.

[18] David Grahame Shane, *Recombinant Urbanism: Conceptual Modeling in Architecture, Urban Design, and City Theory*, Kindle Edition (Chichester: Wiley-Academy, 2005).

[19] Shane associates the work of economists Von Thünen (1826), Weber (1929) and Alonso (1964) with the continuation by other symbolic means of this dominant center as a reservoir of wealth through economic exchange of goods produced and sourced from the hinterland. The 'central business district' is a recognizable symbol of the modern relationship to this 'ceremonial' center.

be rationalized and programmed. Functions are separated following a logic of optimization and linked by communication networks separating different forms of transport. The reservoirs of the vectorial motor are multiplied and linked by movement networks. Activities situate themselves according to particular reservoirs, not only in terms of distance for movement but also within an overall balance between points of production, extraction and exchange.[20]

The ecological model addresses the city as an organism, where urban actors "struggle to maintain a delicate, 'organic' balance."[21] Borrowing from cybernetics and 19th century thermodynamics, the city is viewed as an organism whose metabolism drives towards "balanced flows of energy and materials between the human and natural subsystems of the material realm."[22] Its reservoir's driving force (*puissance motrice*) is the natural world itself perceived as a benevolent force balancing destructive and conservative forces.[23] This balancing force has often been perceived as synonymous with mathematical equilibrium, which addresses this driving force of difference within nature as equations of inputs and outputs and resembles the flow and movement-oriented approach of the city as machine. Challenging this approach, 'the new ecology' underlines the importance of non-equilibrium in the balance of nature.[24] Rather than operate purely according to flows of certain quantities of matter, this approach focuses on the processes and performances of natural and human elements in an ecosystem. Everything has a role and plays a part.

The underground appears differently in each of these models. The city of faith sees the underground as a place of death or rebirth and purification. It is for the most part excluded from the city (which is oriented towards the heavens) or limited to ritual acts. As the main reservoir is the ceremonial center, tied to otherworldliness, the underground as inhabitable space is treated according to local myth and practice.[25] With increasing industrialization, the earth's subsurface entered into a mechanical logic of reservoirs from which resources were extracted for transport and transformation.[26] This logic recalls the two-dimensional relationships explored by early location theory (Von Thünen and particularly Alonso) of extraction,

20 Shane situates the Central Place Theory of economists Walter Christaller and Albert Lösch within the city as machine normative model.

21 Shane, *Recombinant Urbanism*.

22 Sebastian Moffatt and Niklaus Kohler, "Conceptualizing the Built Environment as a Social–ecological System," *Building Research and Information* 36, no. 3 (June 2008): 249.

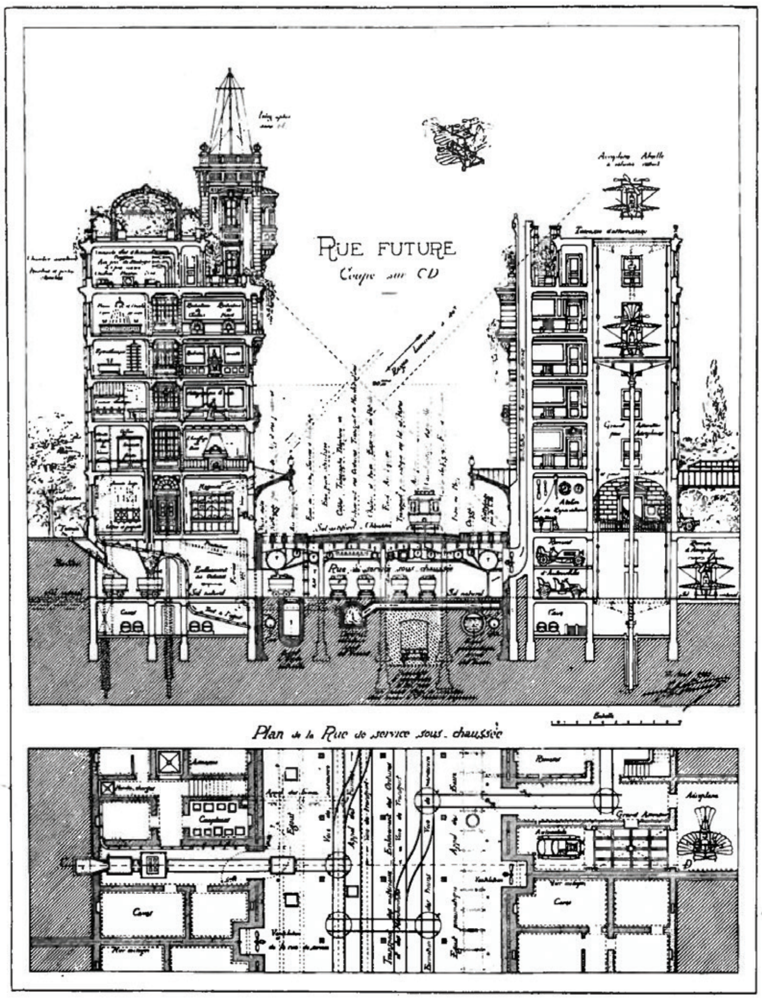
23 Kim Cuddington, "The 'Balance of Nature' Metaphor and Equilibrium in Population Ecology," *Biology and Philosophy* 16, no. 4 (2001): 463–79.

24 S.T.A. Pickett, M.L. Cadenasso, and J.M. Grove, "Resilient Cities: Meaning, Models, and Metaphor for Integrating the Ecological, Socio-Economic, and Planning Realms," *Landscape and Urban Planning* 69, no. 4 (October 2004): 369–84.

25 Shane, *Recombinant Urbanism*.

26 The scientific exploration of the earth's crust did not immediately eclipse the mythical dimension of the underground. With the birth of geological investigations in the 19th century, the earth's crust was equated with a deep time, or an archive of the earth's history. Many people thought geology would turn up the remains of the original sinners having died in the Biblical flood. The bodies that were found, however, did more to support Darwin's theory of evolution. The bodies of extinct species of animals inspired many of the fantastical adventure stories we recognize in the works of Jules Verne, see Williams, *Notes on the Underground an Essay on Technology, Society, and the Imagination*.

Figure 1.1. Eugène Hénard's *Rue Future* (future street) integrating the underground into a mechanical rationalization of flows of materials and people (Hénard 1903/1982).



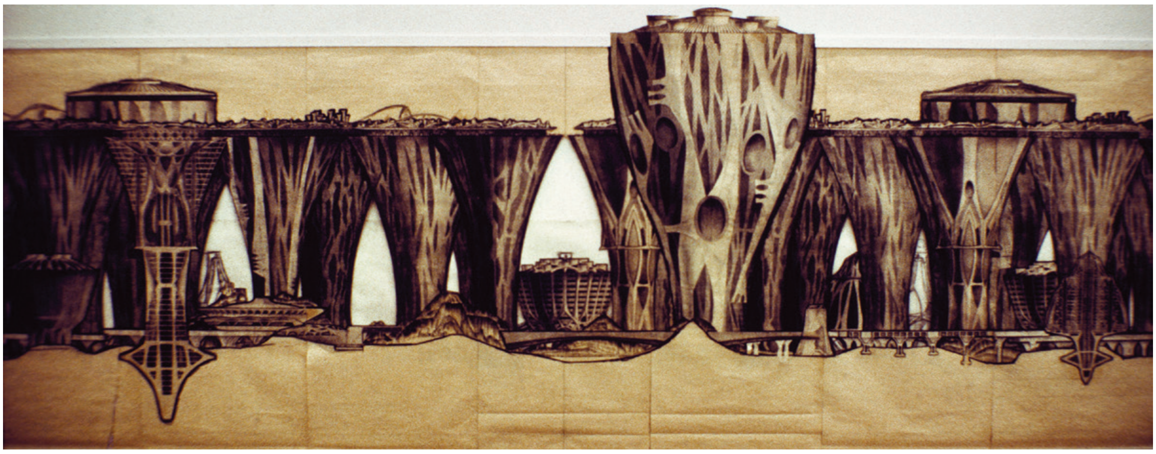


Figure 1.2. Paolo Soleri's 'Ground Villages' for *Mesa City* (1955-1964). Although not really underground, it carves urban forms out of the landscape (source: http://io9.gizmodo.com/paolo-soleri-and-the-cities-of-the-future-509049258, consulted August 29th 2016).

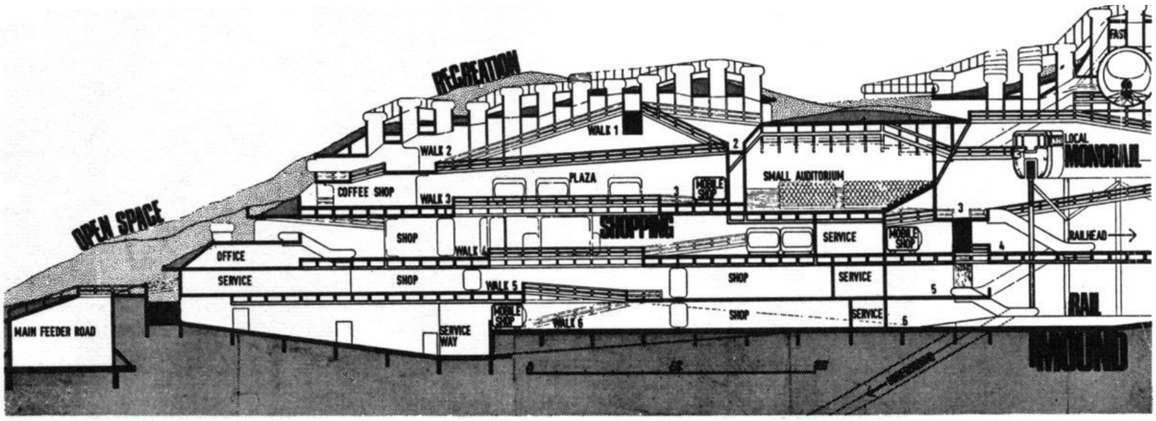


Figure 1.3. Peter Cook of Archigram's *The Mound* (1965). The city is a single artificial building embedded in a landscape void of geological differentiation (Dahinden 1972: 30).

transformation and distribution to the local market.[27] The earliest and best known reflection on the underground in an urban context is the *Rue future* of the Parisian engineer Eugène Hénard (Figure 1.1), which is one of the best examples of both the city as machine normative model and the tendency at the turn of the 20th century to see the city as a unified system.[28] Where this system is not part of the infrastructure of the city, the underground provides a place of escape, with different forms observed on either side of the Atlantic. In North America, the underground serves as a retreat to an organic environment (Figure 1.2), where in Europe it is a retreat to the artificial (Figure 1.3).[29]

With extension of the urban to the planetary scale,[30] the underground is but one layer of all 'altitudes of urbanization'.[31] The emphasis in the ecological model on process and performance means that the underground is included where it clearly has a role. These processes are often surface ones, except for where they have to do with the flows of surface water or the large removal of soils. The underground matters where it participates in an ecosystem, in a linking of processes in a network, where it is already *needed*. It is sometimes labelled in this context as an ecosystemic or infrastructural 'service'.[32] Alternatively, it is an antagonistic force to be avoided and left alone. In practice, most urban projects that have attempted to incorporate larger ecological processes tend to be limited to the near surface and even somewhat scenographic.[33] Projects tend to be oriented towards a single or limited set of pre-defined processes—an approach that does not explore inexistent yet possible dynamics. Part of the limitations of the ecological model is its continuing

27 For illustrations and a more mathematical description, see Juval Portugali, Complexity, Cognition and the City, Springer Complexity (Heidelberg: Springer, 2011).

28 Williams, *Notes on the Underground an Essay on Technology, Society, and the Imagination*; Shane, *Recombinant Urbanism*; Eugène Hénard, *Etudes Sur Les Transformations de Paris, et Autres écrits Sur L'urbanisme*, Collection "Formes Urbaines" (1903; repr., Paris: L'Equerre, 1982).

29 Justus Dahinden, *Urban Structures for the Future* (London: Pall Mall Press, 1972), 30.

30 Brenner and Schmid, "Towards a New Epistemology of the Urban?"

31 Pierre Bélanger, "Altitudes of Urbanization," *Tunnelling and Underground Space Technology* 55 (May 2016): 5–7.

32 Nikolai Bobylev and Ray Sterling, "Urban Underground Space: A Growing Imperative," *Tunnelling and Underground Space Technology* 55 (May 2016): 1–4; Nikolai Bobylev, "Mainstreaming Sustainable Development into a City's Master Plan: A Case of Urban Underground Space Use," *Land Use Policy* 26, no. 4 (October 2009): 1128–37.

33 Shane makes this observation in his review of the ecological approach of landscape urbanism.

reliance on the mechanical model and a misunderstanding of the role of 'function' in nature—placing teleology prior to invariance, which Monod's work had already challenged in the 1950s.

1.3. The informational motor: Substitution and circulation

Serres's third motor is informational.[34] If the first generation of motors transports and the second transforms, the third codes. It combines the flow of messages with the place-holding, substitutive, roles of markers. Where systems thinking and cybernetics establish fixed roles and relationships between predefined elements, Serres seeks a systematization of that which has no (or no recognized) place in the system.[35] In *The Parasite*, he looks at how the presence of the guest at the household dinner table is kept in a delicate balance by the strict conduct in which a meal is offered in return for conversation.[36] The guest must remain in this relationship of the dual vector (giving and receiving) at the risk, for the household, of troubling the internal order and at the risk, for the guest, of no longer being welcome. When the vector becomes unidirectional in the direction of the guest, he or she becomes a parasite, who, in the extreme, may attempt even to usurp the role of the host and redefine the roles of everyone in the household. Through this act, the parasite has introduced something 'foreign' in the system and initiated a recoding. This recoding is a gamble for the parasite, because the household could collapse and then everyone would suffer.

The example of the guest at the dinner table is only an introduction to Serres's exploration of an informational motor. He is interested in the role of the parasite, which in French is also the word used for noise on a channel. In Lucretius's 1st century B.C.E. poem, *De Rerum Natura* [On the Nature of Things], Serres reads an early version of our understanding of the physical world.[37] For Lucretius, everything is born out of a chaos cloud, the elements (atoms) of which 'fall', forming the *clinamen*, a series of laminar (parallel) flows. From this initial orderly directionality, everything is born as a bifurcation or turbulence in this fall. From a chance circumstance in the ordered fall, not the reverse. For Serres, the *ichnography* (which constitutes the integral of all directionality) is rendered *scenography* by an initial angularity in the fall of atoms. The parasite is responsible for such bifurcations. Everything that exists in the world is thus out of equilibrium, which foresees Monod's claim that invariance (the rules or codes) are prior to teleonomy (governing of a system by a final state).

34 Serres, *La Distribution*.

35 "Le problème posé ne serait pas un problème logique, celui de la construction d'un système, mais d'un problème plus général: celui du systématisme d'un grand nombre de systèmes possibles. Peut-on passer de ces nouvelles scénographies à l'ichnographie ? » [The problem is not a logical one of the construction of a system, but a more general problem of the systematism of a large number of possible systems. Can we move from these new scenographies to the ichnography?] Michel Serres, *Le système de Leibniz et ses modèles mathématiques: Etoiles, schémas, points*, 3. éd, Épiméthée (Paris: Presses Univ. de France, 1990).

36 Serres, *The Parasite*.

37 Serres, *The Birth of Physics*.

The probable state of a system is therefore not equilibrium, as it would have been for 19th century physical and statistical thermodynamics, but rather its dissolution and thermodynamic death.[38] This is the view of equilibrium that is found in non-equilibrium versions of ecology where systems are open.[39] For this latter, the open system is importing energy or information that it needs and ejecting as waste that which it cannot use. The system is evolving to avoid death rather than simply returning to a stable state. However, the nature of what is being imported in the fight to remain out of equilibrium is ambiguous. The physicist and information theorist, Léon Brillouin, defined this imported information as negative entropy, or *negentropy*.[40] There are two types of negentropic forms of information: bounded information (that which physically circulates within the system as part of maintenance practices) and free information (that which circulates freely and has not specific meaning or purpose). It is this free information that constitutes, for Serres, the reservoir of the informational motor. It is a capital, an *ichnography*, in which a finite (but large number) of possibilities are encoded. Nothing new comes from the logic of the host and the guest (the bounded information). Novelty is born from free information, the chance circumstance when the roles shift. Negentropy is drawn from the reservoir, the *ichnography* or the noise. Brillouin argued that this novelty, new information born from the negentropy, is not free, but comes with a cost.[41]

The informational motor is powered by negentropic information, drawn from surrounding seas of noise (entropy or the ichnography). It is a motor composed of transmitted messages and relay points, of quasi-objects, quasi-subjects and quasi-collectives. In developing the figure of the quasi-object, Serres returns regularly to the game of soccer.[42] The game is maintained by the passing of a ball, which persists as long as the ball is kept in play. The movement of the ball establishes particular relationships between the players, the team and the spectators. The ball's status depends entirely on the interiority of these relations. This establishes it as a quasi-object. The fact that the players themselves depend on the movement of the ball for their 'positions' and their status on the field designates them as quasi-subjects. The objectivity of the ball and the subjectivity of the players is maintained only in this dynamics of the ball in play. The very constitution of the game, of the collectives of players, each team, and of the spectators is maintained by the passing of the ball. The pass builds a quasi-collectivity. The game is of course governed by rules, which constitute the bound information and ensure its

[38] Léon Brillouin, *Science and Information Theory*, Kindle Edition (orig. 1962), 2013, http://public.eblib.com/choice/publicfullrecord.aspx?p=1897478.

[39] Pickett, Cadenasso, and Grove, "Resilient Cities."

[40] Brillouin, *Science and Information Theory*.

[41] Even if that cost is a quantum of light, as he argues when working through the ability of Maxwell's demon to "freely" move electrons from one heated chamber to another, in contradiction to the second law of thermodynamics which postulates that systems move towards entropy or molecular disorder. Ibid.

[42] Serres, *Genèse*.

perpetuity. Parasitizing, for instance refusing to pass the ball, is met with the ire of the team or with being ejected from the game, such as when a player appears to have deliberately touched the ball with her hand. The game as such limits free information as much as possible.

The game of soccer is a highly controlled microcosm and has its limits as an operational metaphor for the informational motor. Noise, parasites—that which is outside the commonly established rules—are strictly regulated by lines ('guarded' by linesmen), referees, barriers between the players and spectators. It is an *oikos* whose language (*logos*) and laws (*nomos*) produce a very particular ecology and economy. To take these roles as fixed within the game as a 'performance' would reduce our point of view to the epistemic (single viewpoint) or the diastemic (the dual viewpoint). We remain ignorant to substitution and *lieutenancy*.[43] When a crazed fan runs naked across the field, a 'foreign' body (free information) has invaded the game and the role of spectator and entertainer is reversed. The players become witnesses to an event. Such moments are possible or expected. Security agents quickly restore order and everything resumes its place. Nothing new.

Novelty comes from the as-yet-unheard message in the noise. Lest the examples of the dinner table and the ball game eclipse the ichnography (the material) and are interpreted as limited to particular scenographies (sociology, anthropology, etc.), this noise can be understood as *mass*. Mass, as opposed to matter, is "raw, testimony to a real that's independent of the mass of humanity, crowds and messages."[44] An earthquake or landslide sends mud and marl over a bed of quaternary alluvium. The course of a river changes. Existing vegetation is wiped out to be gradually replaced by different plants and animals. The event of the landslide reconfigured a place (substituted one for another). Mass "conditions the existence of the things of the world that conditions us, and its permanence conditions the universe."[45] Rather than address this mass epistemically or diastemically, the informational motor multiplies the points of reference. There is no single message in the noise; no single form in the mass. Free information enters the system as negentropy from the entropy (*ichnography*) and becomes bounded (as *scenography*) within the constraints of invariance—understood as the *orthography*.[46] The reservoir of free information makes substitutions possible. Each point can become a 'here' and the system can be recoded. It is *choreostemic*.[47] It is the actualization

[43] Lieutenancy is literally a place (lieu) holder (tenant), see Douglas Harper, "Lieutenant," *Online Etymology Dictionary*, 2016, http://etymonline.com/index.php?allowed_in_frame=0&search=lieutenant.

[44] Matter, Serres reminds us, has no rigorous physical definition and remains "an empty metaphysical word", Serres, *Statues*, chap. 5.

[45] Ibid.

[46] Vera Bühlmann, "Architectonic Disposition: Ichnography, Scænography, Orthography," in *The Posthuman Glossary*, ed. Rosi Braidotti and Maria Hlavajova, Bloomsbury, 2016, Forthcoming.

[47] "from the Greek choreia for 'dancing, (round) dance', referring to an unfixed point loosely moving within an occurring choreography, but without being orchestrated prior to and independently of such occurrence" Vera Bühlmann, "Primary Abundance, Urban Philosophy—Information and the Form of Actuality," in *Printed Physics: Metalithikum I*, ed. Vera Bühlmann and Ludger Hovestadt, Applied Virtuality Book Series, v. 1 (Vienna: Springer, 2013), 125.

of the virtual within a spectrum of orthographic potential, an "as-yet-unspecific potential-related abundance."[48]

1.4. Informational motors of the urban: Economies of communication

In response to the weakness and relative inflexibility of the normative models of the city of faith, the city as machine and the ecological city, urban theory departed from holistic models and sought to identify the basic elements comprising the city. Referring in particular to the work of Lynch, Rowe and Koetter and Paola Viganò, Shane identifies three main elements that have pervaded elementary thinking: the enclave, the armature and the heterotopia.[49] The enclave is an element of centralization and concentration, like squares, places, bounded spaces. The perimeter is often controlled in some way by rules, guardians or walls. The armature is a sorting device, linking the enclaves and organizing the relationships between them. The classic examples are streets, arcades, interior corridors and skyscrapers (vertical armatures). The heterotopia, borrowed from Michel Foucault, is "a place that mixes the stasis of the enclave with the flow of an armature, and in which the balance between these two systems is constantly changing."[50] Heterotopias include Foucault's best known examples of the prison and the hospital, but also shopping malls, amusement parks and cruise ships. They challenge the dominant enclave-armature order.

With the armature, enclave and heterotopia, Shane tries to move beyond the limits of morphology and typology—the tendency to produce "detailed classifications of buildings and open spaces."[51] Such libraries and taxonomies of solids and voids offers "a speedy response and a standardized product", but they suffer from "inflexibility, lack of control by the user, [and] the elimination of variety and choice."[52] They tend to fix the identity of the elements of a city, no matter how exhaustive and long the list.[53] There is a tendency to identify and reproduce types as necessary (rather than contingent) stabilities. This results in a conflict between those typomorphological elements that are allowed or elevated to artistic prominence and those that are considered *non-discursive*[54] or developed from a *spontaneous consciousness*.[55] By attempting to fix types as bounded information, the opportunity to free information, for that which is outside the

48 Ibid., 133.

49 Shane refers specifically to Lynch's The Image of the City (1960), Colin Rowe and Fred Koetter's Collage City (1979) and Paola Viganò's La città elementare (2000), presented in, C Shane, *Recombinant Urbanism*.

50 Ibid., chap. 3, Kindle Edition.

51 Anne Vernez Moudon, "Getting to Know the Built Landscape," in *Ordering Space: Types in Architecture and Design*, ed. Karen A. Franck and Lynda H. Schneekloth (New York: Van Nostrand Reinhold, 1994), 289.

52 David Grahame Shane, "Transcending Type: Designing for Urban Complexity," *Architectural Design* 81, no. 1 (January 2011): 128.

53 Christopher Alexander's Pattern Language identifies 253 patterns, Christopher Alexander, Sara Ishikawa, and Murray Silverstein, A Pattern Language: Towns, Buildings, Construction (New York: Oxford University Press, 1977).

54 Bill Hillier and Julienne Hanson, *The Social Logic of Space* (Cambridge: Cambridge University Press, 1984).

55 Gianfranco Cannigia and Gian Luigi Maffei, *Architectural Composition and Building Typology: Interpreting Basic Building*, Sagge E Documenti (Alinea Editrice) 176 (1987; repr., Florence, Italy: Alinea, 2001).

typical or formal language (*logos*), is severely limited. Shane hints at a return to the mass that Serres speaks of, arguing that "types emerge from a flow of energy and pressure, engineered by particular urban actors as specific times to deal with particular situations."[56] He is aware of the contingency of the typical and morphic. But the motor he constructs with the three elements is a cybernetic (systemic) one—certain places are armatures, some enclaves and others heterotopias and they behave as such. It is a logic of combinatorics, of mechanical movements and 'pressures' that condition situations. It lacks the informational motor's operation of substitution.

Within an informational motor of the urban, the enclave, armature and the heterotopia are like complexions, with the first two, markers and messages, organizing bounded information. The heterotopia reprograms by coding or importing free information. It can be as much about correction (e.g. prisons) as it can be about emancipation (e.g. amusement parks). But as complexions, these 'elements' would actually be "discrete configurations of the quantized physical system".[57] The enclave expresses 'centrality', the armature 'linearity' and the heterotopia as heterotopiality. In Platonic philosophy, these complexions concern the status of universals. Universals may be abstract or concrete. Simply put, abstract universals are not self-participating and are synonymous with ideal forms.[58] The ideal form of a house is never fully instantiated. Much typo-morphological work churns out taxonomies of these abstract universals. Concrete universals are self-participating, meaning first of all that they can never exist externally to the set from which they emerged. They are a more contingent understanding of universality. The concrete universal of a house would be the house-ness in which a set of houses participate. Each house factors in to a choreostemics of house-ness.

The concrete universal draws attention away from the normative claims made by urban theory about city form, to the ways laws are locally configured. It is an economy, understood etymologically as *oikonomia*, "the worldly manifestation of a given order."[59] In Ancient Greek, *oikoi* also referred to the seasons, around which all events were ordered. So, "to know what to do in the *oikonomia* was basically to know where the sun stood."[60] In the first two motors (of transport and transformation), it is clear where the sun, the source or the reservoir is. The information motor, however, multiplies this reservoir to near infinity, turning the *oikos* into local pockets of information or negentropy, fluctuating according to law-like rhythms

[56] Shane, "Transcending Type," 133.

[57] Brillouin conceived of entropy as the integral of these complexions. It is therefore potentiality, the "entropy of the system" which is an "extremely large, but finite" number, see Brillouin, *Science and Information Theory*; Vera Bühlmann, "Negentropy," in *The Posthuman Glossary*, ed. Rosi Braidotti and Maria Hlavajova, Bloomsbury, 2016, Forthcoming.

[58] For Ellerman, this type of universality is captured by set theory, whereas concrete universals are the domain of category theory, see David Ellerman, "On Concrete Universals: A Modern Treatment Using Category Theory," *SSRN Electronic Journal*, 2014.

[59] Till Düppe, *The Making of the Economy: A Phenomenology of Economic Science* (Lanham, Md.: Lexington Books, 2011).

[60] Ibid.

(*nomos*). In the constitution of the urban economy (taking this word to mean the manifested order), encounter and interaction have been seen as dominant egalitarian forces. The street, for instance, as the public place *par excellence* is idealized as a place of encounter, whose form is stable and calibrated.[61] Encounter becomes equated with equality and as a cure to avoidance (synonymous with anti-social behavior).[62] Differentiations of mass, whether populations of people or the laying or carving of stone, always articulate a combination of encounter and avoidance. The relation between the two is therefore "not a binary or logical opposition of either/or, but rather a saturated relation of both/and."[63] Heterotopiality is a perfect example of this saturation. Certain places orchestrate an encounter of one type at the expense of an avoidance of another.

Together, avoidance and encounter constitute a basic economy of communication. Not in the sense of speech and language (a *logos*), but a *communas*, in the sense of that which is held in common or shared. If there is a logic of this sharing, if it has a *logos*, then this is internal to this economy and ciphered. It is the *nomos* of this *oikos*. As Serres claims in *The Birth of Physics*, everything exists as a black box, which contains the mystery and secret of its origin: "nature is hidden twice", under a cipher and a then a dexterity.[64] The fight against thermodynamic death and dissolution requires a persistent folding and founding according to certain law-like invariances. Information, novelty, enters and is enfolded, encoded. Scientific practices seek to decipher and give language to these observed regularities, scenographies of an ichnography. The ichnographic noise of an economy of communication provides a reservoir for the sociological and political. But the reservoir of this economy is the mass, of populations and matter, which it sorts and upon which it leaves traces. Experimentation and investigation do not read back a *logos* (the symmetry of reading and writing), but attempt to decipher the *graphein* (the asymmetry of the trace and that which left it).

The informational motor of the urban, like the other two motors, can be harnessed. The deciphering of the economy of communication seeks to identify the concrete universals of avoidance and encounter. The mass of the urban form encodes these universals in the materiality of the city. Spatial practices operate on this mass and contingently decipher the ichnography. In the act of deciphering, in the fact that this particular congealing of mass has no single logic, lies the potential for multiple meanings, recoding, and algebraic substitutions.[65] Speaking of urban infrastructure, Keller

[61] Hénaff, *La ville qui vient*.

[62] Daniel Koch, "On Avoidance: Reflections on Processes of Socio-Spatial Structuring," *Civil Engineering and Architecture* 4, no. 2 (April 2016): 67–78.

[63] Ibid., 76.

[64] Serres, *The Birth of Physics*.

[65] This is one of the limits of seeing spatial configuration, or the differentiation of mass in human settlements as governed by a social logic. The economy of movement as Hillier defines it in Space is the Machine addresses this differentiation of mass as a reservoir for a motor of transport governed by a single scenography and logos (socio-logy). In an economy of communication, the economy as a worldly order is prior to any logos that presumes to speak its language. Hillier and Hanson, *The Social Logic of Space*; Bill Hillier, *Space Is the Machine: A Configurational Theory of Architecture*, Electronic Edition (1996; repr.,

Easterling refers to the ichnography as 'disposition.' It is what is "hidden in the folds of infrastructure space" and is a "latent potential or tendency that is present even in the absence of event."[66] Disposition is not a single potential, a single actualization but the bundle of all that could or could not be actualized, what Giorgio Agamben calls *potentiality*. If encounter is a potential, avoidance is also a potential and their "saturated relation"[67] would constitute the potentiality of the economy of communication. The emancipatory possibility of potentiality lies in the capacity to articulate its potential-not-to-be.[68] That is, the cost of encounter is avoidance and vice versa, but their inseparability means that no price can be placed, the accounts never balanced. The inability to bring them into perfect proportion is what keeps possibility and potentiality open.

1.5. Resources to needs: Mapping and deciphering the potentiality of the urban volume

This dissertation is interested in a particular mass, that of the urban volume, as both something encoded and as something to offer up for creative recoding. The underground tends to be addressed as a reservoir for only the first two motors and this has proved problematic. The engagement has been sectorial, organized from a single point. Conflicts have occurred between competing uses. Mexico City is well known for its century-long problem of subsidence. Heavy pumping of the urban aquifer has led to a decrease in groundwater levels and a gradual drying up and sinking of the highly compressible lacustrine sediments underlying much of the urban area.[69] In Paris, a similar problem led to a moratorium in the 1960s on overexploitation of the aquifer, which resulted in an inadvertent rise of the water table and a flooding of buildings with basements built with respect to former groundwater levels.[70] Paris, like New York and many other cities, suffers from a congestion of infrastructure beneath its streets. The collection, visualization and interpretation of data tends to occur within disciplinary or departmental corners.[71] Within this paradigm, urbanization tends to first formulate needs and problems and only later examines the potential of resources to meet or solve them.[72]

Cambridge: Cambridge University Press, 2007).

66 Keller Easterling, *Extrastatecraft: The Power of Infrastructure Space*, Kindle Edition (Brooklyn: Verso, 2014), chap. 2.

67 Koch, "On Avoidance," 76.

68 Giorgio Agamben, *Potentialities: Collected Essays in Philosophy*, ed. Daniel Heller-Roazen, Meridian: Crossing Aesthetics (Stanford, Calif: Stanford University Press, 1999).

69 Dalia Ortiz-Zamora and Adrian Ortega-Guerrero, "Evolution of Long-Term Land Subsidence near Mexico City: Review, Field Investigations, and Predictive Simulations: Long-Term Land Subsidence," *Water Resources Research* 46, no. 1 (January 2010).

70 Pascal Blunier, "Méthodologie de Gestion Durable Des Ressources Du Sous-Sol Urbain" (Doctoral Dissertation, EPFL, 2009), http://library.epfl.ch/theses/?nr=4404.

71 Grégoire Feyt, "Les visages et usages de l'information géographique dans le processus de décision territoriale," in *Les SIG au service du développement territorial*, ed. Olivier Walser et al. (Lausanne: Presses Polytechniques et Universitaires Romandes, 2011).

72 A. Parriaux, L. Tacher, and P. Joliquin, "The Hidden Side of Cities—towards Three-Dimensional Land Planning," *Energy and Buildings* 36, no. 4 (April 2004): 335–41.

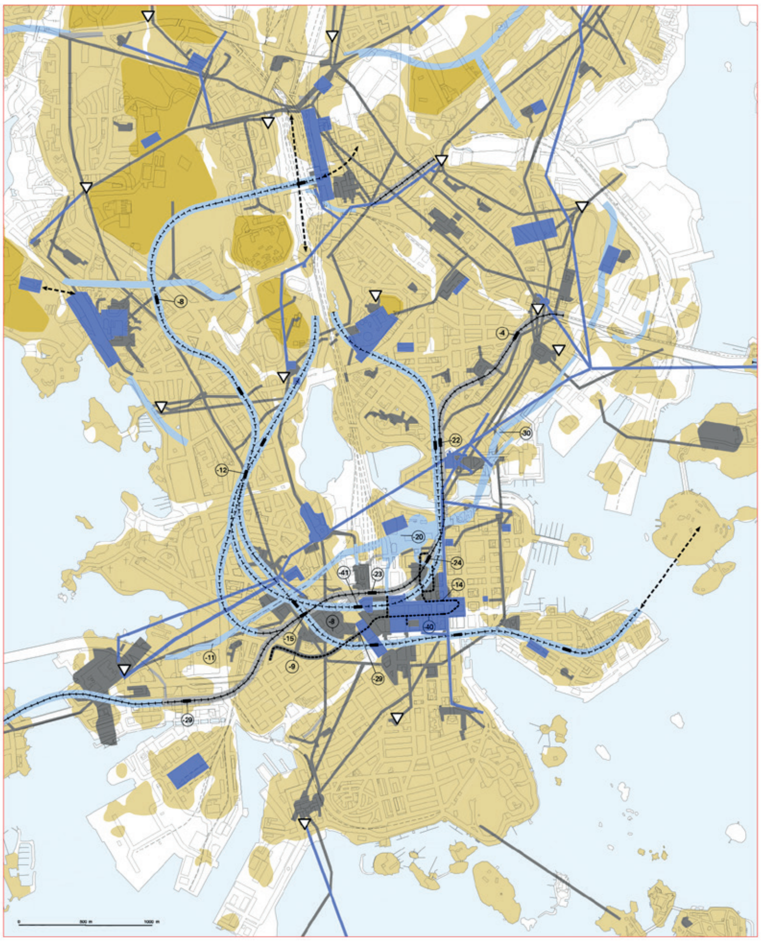


Figure 1.4. Helsinki Master Plan with reserved spaces marked in areas of suitable cavern spaces with existing and future tunnels (source: Vähäaho, 2009).

The response to the fragmentation of the urban volume has been to promote the integration of underground resources into urban masterplans.[73] This can be seen on the one hand as the continuation of the normative model of the city as a machine, of which important examples include the work of Tokio Ojima and Édouard Utudjian's GECUS in the 20th century.[74] On the other, it is indebted to the ecological model and the work of Ian McHarg, who increased the awareness of geology and natural processes for urban planning and introduced the map overlay method.[75] The maps that receive the most attention from urban planners tend, however, to remain oriented towards underground space. The Helsinki rock cavern masterplan (Figure 1.4) is oriented towards potential cavern spaces.[76] Hong Kong is currently drawing up a similar cavern masterplan to develop additional space and Singapore is drawing up a multi-level zoning plan.[77] Cities like Montreal and Toronto, which are often

73 Bobylev, "Mainstreaming Sustainable Development into a City's Master Plan."

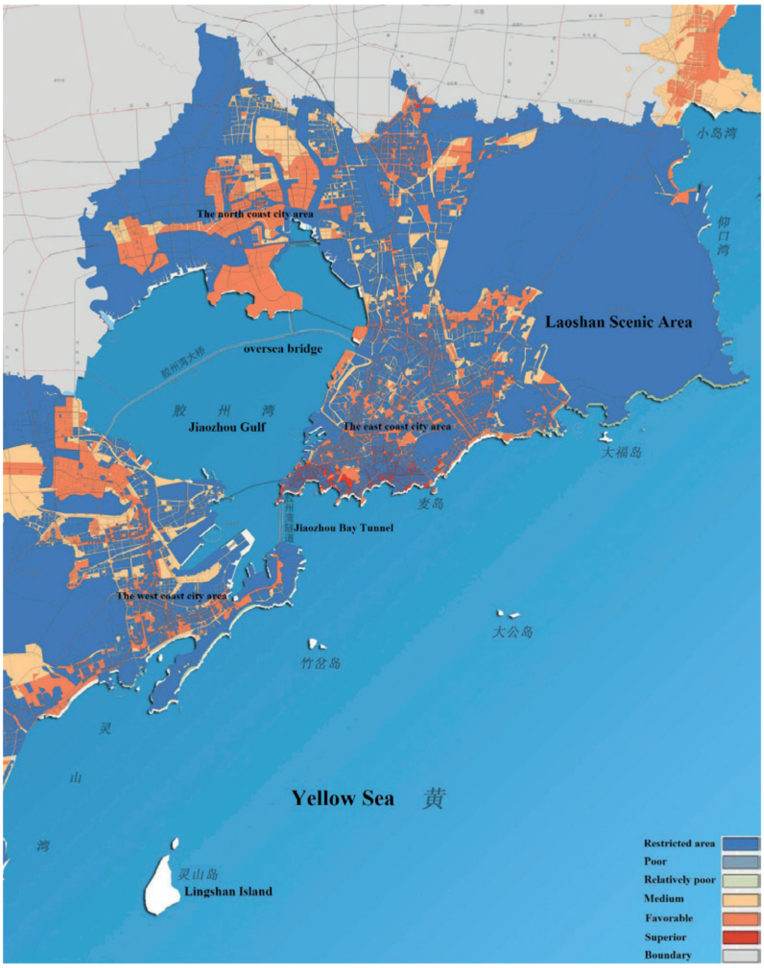
74 Edouard Utudjian, *L'urbanisme souterrain*. (Paris: Presses universitaires de France, 1952); Sabine Barles and André Guillerme, *L'urbanisme souterrain* (Paris: Presses universitaires de France, 1995); Gideon Golany and Toshio Ojima, *Geo-Space Urban Design* (New York: John Wiley, 1996).

75 Ian L McHarg, *Design with Nature* (Garden City, N.Y.: Published for the American Museum of Natural History by the Natural History Press, 1969); Wybe Kuitert, "Urban Landscape Systems Understood by Geo-History Map Overlay," *Journal of Landscape Architecture* 8, no. 1 (May 2013): 54–63.

76 Ilkka Vähäaho, "Underground Masterplan of Helsinki: A City Growing Inside Bedrock," Extract from the Underground Masterplan of Helsinki (Helsinki: City of Helsinki, 2009).

77 Chiara Delmastro, Evasio Lavagno, and Laura Schranz, "Underground Urbanism: Master Plans and Sectorial Plans," *Tunnelling and Underground Space Technology* 55 (May 2016): 103–11.

Figure 1.5. Qingdao Case Study underground space potential map at 0-10 m deep. Potential ranges from lowest (blue) to highest (red). The surface urban conditions are only taken as a constraint to potential, not constitutive of it (Jing-Wei Zhao et al 2016, p.297)).



cited in the literature as exemplary cases of underground urbanism, remain space-oriented. Their expansion has been driven more by private investment than a masterplan or a diagnostic map of space potential—potential was simply locally intuited case by case.[78] In China, eleven cities are in some way incorporating underground space in their masterplans.[79] A case study carried out in Qingdao visualizes construction potential as geographically situated and multi-level (Figure 1.4). However, the geological formations and groundwater are only incorporated as constraints on the space resource, not as potential resources in themselves.

The Deep City project at the École polytechnique fédérale de Lausanne (EPFL) was launched by the Laboratory of Engineering and Environmental Geology (GEOLEP) in 2005. It seeks to reverse the trend of looking at underground resources in direct response to pre-defined needs. The 'resources to needs' paradigm it proposes consider four resources—buildable space, geomaterials,

78 Ahmed El-Geneidy, Lisa Kastelberger, and Hatem T. Abdelhamid, "Montréal's Roots: Exploring the Growth of Montréal's Indoor City," *Journal of Transport and Land Use* 4, no. 2 (August 18, 2011): 33–46; Michel A Boisvert, *Montréal et Toronto : villes intérieures* (Montréal: Presses de l'Université de Montréal, 2011); Pierre Bélanger, "Underground Landscape: The Urbanism and Infrastructure of Toronto's Downtown Pedestrian Network," *Tunnelling and Underground Space Technology* 22, no. 3 (May 2007): 272–92.

79 Jing-Wei Zhao et al., "Advances in Master Planning of Urban Underground Space (UUS) in China," *Tunnelling and Underground Space Technology* 55 (May 2016): 290–307.

groundwater and geothermal energy—as reservoirs of potential.[80] A multi-resource and multi-use approach to the underground is considered sustainable because it facilitates long-term management and an early response to potential conflicts and synergies. The underground is addressed as a strategy to increase urban compactness, increase walkability and the accessibility of urban activities. It is an alternative to building upwards, with the objective of concentrating urban activities above and below the street level at lower surface densities. For this reason, the project has been particularly interested in urban activities like food and retail, which are often located in the underground in pedestrian passages or metro stations or in underground conditions with only electric or zenithal lighting (e.g. malls, cinemas, theaters). The project has explored, both in scientific literature and in the experiences of past cities, the different types of interactions that occur between the resources and developed a method for integrating multiple resources in a single map.[81] The mapping process has been tested on particular locations in Geneva and on the Chinese city of Suzhou.[82]

The Deep City mapping procedure, which will be described in more detail at the beginning of Chapter 3, imports georeferenced data on the four resources into a geographical information system (GIS) and classifies the geological formations according to their characteristics into a series of geotypes. Geotypes have the advantage of being both easier to work with for urban planners or non-specialists in geology and in being categories that can facilitate comparisons by geologists of the geological conditions of different cities.[83] The geotypes are evaluated in their potential suitability for each resource using either empirical evidence (such as the thermal conductivity of geological formations) or expert opinion (evaluation of the suitability of geotypes for geomaterial use of buildable space). Expert opinion is quantified using the Analytic Hierarchy Process, in which pairwise comparisons between geotypes are placed in a comparison matrix.[84] The solution of this matrix produces a single suitability vector which places the geotypes on a relative scale (ordinal scales tend to poorly represent the proportional relationships between compared elements). The geotype suitability vector becomes one of several criteria in evaluating the overall potential for each resource. The contribution of each criterion is again situated on a relative scale using pairwise comparisons.

80 A. Parriaux et al., *Projet Deep city : ressources du sous-sol et développement durable des espaces urbains* (Lausanne: vdf Hochschulverlag AG an der ETH Zürich, 2010); Parriaux, Tacher, and Joliquin, "The Hidden Side of Cities—towards Three-Dimensional Land Planning."

81 Blunier, "Méthodologie de Gestion Durable Des Ressources Du Sous-Sol Urbain."

82 Ibid.; Pascal Piguet et al., "A New Energy and Natural Resources Investigation Method: Geneva Case Studies," *Cities* 28, no. 6 (December 2011): 567–75; Huanqing Li et al., "An Integrated Planning Concept for the Emerging Underground Urbanism: Deep City Method Part 2 Case Study for Resource Supply and Project Valuation," *Tunnelling and Underground Space Technology* 38 (September 2013): 569–80; Pascal Piguet et al., "A New Energy and Natural Resources Investigation Method: Geneva Case Studies," Cities 28, no. 6 (December 2011).

83 A. Parriaux and Pascal Turberg, "Les Géotypes, Pour Une Représentation Géologique Du Territoire," *Tracés* 133, no. 15–16 (2007): 11–17.

84 Thomas L. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation* (New York ; London: McGraw-Hill International Book Co, 1980).

The production of each individual resource potential is relatively straightforward. However, it is the combined potentials that are at stake for providing a source of novelty. The collapse of the four into a single map faces the challenge of how to aggregate them while preserving the legibility of the map and the richness of the information provided. The AHP was in fact adopted as a convenient decision-making aid. It proposes an aggregation process that is oriented to a particular objective. The use of objectives (or are particular teleology) is compatible with the systemic approach adopted by the project in its infancy.[85] However, to be a reservoir for an informational motor of the urban, the maps need to be able to capture a potentiality without orienting it towards a particular objective. The continuation of the map overlay tradition initiated by Ian McHarg does not address the map as a passive representation (*scenography*) of the territory, but as creating the "conditions for the emergence of new realities," as a process that 'finds' and then 'founds'.[86] In constituting a reservoir for urban potentiality, it is not intended only for the deterministic practices of vectorial and transformational motors, but also an intuition and novelty-based recoding of the informational motor.

In the examples of underground mapping provided above, the 'mass' of the existing urban form and the potentiality it encodes is entirely excluded. The Helsinki plan only includes existing underground structures and potential cavern entry points.[87] The Hong Kong cavern master plan identifies openings and land ownership status.[88] The method used in the Qingdao study includes distributions of land uses, population densities, transit networks, or property status, but these are understood as indicators of possible demand.[89] Lu and colleagues, in their rail station case study, only evaluate geological suitability, independently of the station's urban context.[90] The sectorial nature of the maps, carried out by engineers and geologists, or by teams in departments with precisely defined responsibilities, means that the urban form is excluded as the purview of different disciplines or departments. The Deep City project investigated the impact of geological and urban conditions on the feasibility of a series of alternative surface and subsurface commercial projects, finding that the geological and urban context (captured as land value) directly condition underground potential.[91]

85 Based notably on Jean Louis Le Moigne, *La théorie du système général : théorie de la modélisation* (Paris: Presses universitaires de France, 1977).

86 James Corner, "The Agency of Mapping: Speculation, Critique and Invention," in *Mappings*, ed. Denis E. Cosgrove, Reprint, Critical Views (London: Reaktion Books, 2002), 214–300.

87 Ilkka Vähäaho, "An Introduction to the Development for Urban Underground Space in Helsinki," *Tunnelling and Underground Space Technology* 55 (May 2016): 324–28.

88 Mark Wallace, K. J. Roberts, and V Lau, "A Geographic Information Systems Approach for Regional Cavern Suitability Mapping for Hong Kong," in *Underground Space: Planning, Administration and Design Challenges* (14th World Conference of ACUUS, Seoul, 2014).

89 Zhao et al., "Advances in Master Planning of Urban Underground Space (UUS) in China."

90 Zhongle Lu et al., "Quantitative Assessment of Engineering Geological Suitability for Multilayer Urban Underground Space," *Tunnelling and Underground Space Technology* 59 (October 2016): 65–76.

91 Pierrick Maire, "Étude multidisciplinaire d'un développement durable du sous-sol urbain. Aspects socio-économiques, juridiques et de politique urbaine" (Doctoral Dissertation, Swiss Federal Institute of Technology Lausanne (EPFL), 2011).

The case study of Suzhou, however, relegated this potential to demand criteria, rather than look at land value or centrality (a proxy in certain conditions for land value).[92] By addressing it as a 'demand', the urban form is turned into a passive reservoir of needs and necessities. As this dissertation will explore, the urban form cannot be limited to an indicator of necessity, but a reservoir of potential that, with the geological conditions, constitutes the potentiality of the urban volume. The next chapter will investigate this urban potential within a particular economy of communication, the Montreal Indoor City.

92 Li et al., "An Integrated Planning Concept for the Emerging Underground Urbanism."

Chapter 2

The Montreal Indoor City

A Spatial Economy of Encounter and Avoidance

2.0 Introduction

Underground spaces are often addressed in everyday discourse and in the scientific research as separate from the surface. Commercial spaces, which are the most common underground spaces frequented by the public, are rarely isolated in basements or in cavern spaces, but are linked to larger networks of underground transport or indoor, multi-level malls. Sometimes these networks of public and semi-public pedestrian space, even connect to cultural spaces, office buildings and housing developments.

Montreal, Canada, with its Indoor City, is a mixture of all of this. However, like much of the underground, it has been up until now analyzed separately from the surface and the 'outdoor city'. By situating the Indoor City in its urban context, the study presented in this chapter tries to address underground spaces, particularly food and retail spaces, as integral parts of a spatial economy of encounter and avoidance. Such an economy is first and foremost dependent on the opportunity for movement and visual connection. Rather than rely on existing typomorphological descriptions of volumetric spaces, this chapter will derive eight original configurational categories from the current distributions of centrality at multiple scales, before investigating their contribution to rental values using methods borrowed from spatial econometrics and geographically weighted regressions.

The philosophical stakes laid out in the first chapter have practical applications for the empirical work carried out in this chapter. These will be discussed in more depth when looking at the forms spatial models take in previous studies of the underground and the statistical methods used to examine the relationship between spatial configuration and a particular spatial phenomenon. Therefore, even as methods are adopted from spatial econometrics, some subtle changes are made that will deviate from more orthodox applications of regression analysis. These are discussed and taken into consideration when interpreting the results of the analysis, but are necessary to provide an original account of the underground spaces and spatial configuration that sheds some of the baggage inherited from dominant paradigms.

2.1 Deciphering the heterotopiality of indoor pedestrian spaces: State of the art

Indoor pedestrian spaces are commonly understood as heterotopic versions of the street where the rules or practices of avoidance and encounter shift. The parasitic nature of this interiorization of publicly accessible space has been criticized for articulating extremes of avoidance, "emptying of [outdoor] public spaces"[1] and excluding particular people.[2] At the same time, the development of commercial and other types of spaces underground is being promoted as a means to increase urban density where land is scarce and where transport or other types of spaces are already being constructed underground.[3] Proponents see underground spaces as offering a complementary strategy for creating encounters through increased accessibility to activities. This involves addressing both the surface and subsurface as coextensive.[4] They together establish an economy of communication. The attention underground spaces has received in the media with the 'Lowline' in New York and the Earthscraper competition project proposed for Mexico City attests to the continuing fascination society has for these spaces where conditions of light, air and horizon are destabilized and reconfigured.[5] The question that remains unanswered is not whether underground and indoor spaces are good or bad neighbors, but rather, from the point of view of an economy of communication, how do they produce a 'neighborliness' and what is this latter's contribution to their success as places endowed with an exchange value.

The literature addresses the underground in part through its forms and aesthetics, as a place set apart from the surface. Architect John Carmody proposes a classification of axonometric drawings of enclave-like spaces developed when investigating the morphology of underground spaces and the linear (armature-like) strategies for entering them within a fictional urban context. [6] Pierre von Meiss examines several built projects and observes a series of different

1 Jan Gehl, *Life between Buildings : Using Public Space* (New York: Van Nostrand Reinhold, 1987), chap. 3.

2 David L. Uzzell, "The Myth of the Indoor City," *Journal of Environmental Psychology* 15, no. 4 (December 1995): 299–310.

3 Nikolai Bobylev and Ray Sterling, "Urban Underground Space: A Growing Imperative," *Tunnelling and Underground Space Technology* 55 (May 2016): 1–4; International Tunnelling and Underground Space Association, "Report on Underground Solutions for Urban Problems," April 2012; Pierre von Meiss and Florinel Radu, eds., *Vingt mille lieux sous les terres : espaces publics souterrains* (Lausanne: Presses Polytechniques Universitaires Romandes, 2004).

4 Monique Labbé, "Offre et demande d'espace souterrain," in *Vingt mille lieux sous les terres : espaces publics souterrains*, ed. Pierre von Meiss and Florinel Radu (Lausanne: Presses Polytechniques Universitaires Romandes, 2004), 25–36.

5 Lowline in New York: http://thelowline.org/; Earthscraper in Mexico City: http://www.archdaily.com/156357/the-earthscraper-bnkr-arquitectura

6 "Design Principles for People in Underground Facilities," in *Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces*, ed. John C. Carmody and Raymond Sterling (New York: Van Nostrand Reinhold, 1993), 135–310.

strategies for both directly and symbolically organizing the transition from the surface to subsurface.[7] Von Meiss, as well as Angus Carlyle, evoke several design considerations in inspiring confidence and a general sense of well-being to 'counter' the effect of being underground, from color choices to specific patterns emphasizing verticality.[8] If these studies approach the underground through disciplinary expertise, three other studies address underground spaces from the point of view of people who frequent them. Two of these investigated positive and negative perceptual aspects of underground transport spaces using interviews, finding that access to and the context within which the metro stations and parking garages are situated were determining factors along with spaciousness and the ease of surveying most of the underground space at once.[9] The third, using commented walks, suggests that perceptions change dynamically with movement.[10]

These studies, however, tend to examine underground spaces in isolation from their specific spatial contexts and to produce classifications of ideal (or abstract) types. Like spaces developed on the surface, those that are underground, despite morphological or typological similarities, configure the logics of encounter and avoidance differently with neighboring spaces. Von Meiss's work highlights the importance of spatially organizing sequence and movement. Durmisevic observes how metro stations set people (and spaces) in relation based on visual field. Maire's interviews of parking garage users show how the aesthetic conditions of the space are less important than the locational convenience within their daily travel.[11] Chelkoff and Thibaud's exploratory study using commented walks by people in the Châtelet-Les-Halles metro station and underground portion of the Louvre museum in Paris stands out in its ability to tease out the contingency of aesthetic appreciations, which are conditioned by cumulative sequences of movement and experience. [12] Their observations raise doubts about studies trying to make general claims about the psychological impacts that certain colors or patterns may have on psychological responses. Interiority

7 "Entre le dessus et le dessous," in *Vingt mille lieux sous les terres : espaces publics souterrains*, ed. Pierre von Meiss and Florinel Radu (Lausanne: Presses Polytechniques Universitaires Romandes, 2004), 87–93.

8 Pierre von Meiss, "La cohérence verticale," in *Vingt mille lieux sous les terres : espaces publics souterrains*, ed. Pierre von Meiss and Florinel Radu (Lausanne: Presses Polytechniques Universitaires Romandes, 2004), 109–14; Angus Carlyle, "Beneath Ground," in *City Levels*, by Ally Ireson and Nick Barley (Basel: Birkhäuser, 2000), 96–114.

9 Sanja Durmisevic, "Perception Aspects in Underground Spaces Using Intelligent Knowledge Modeling" (Doctoral Dissertation, TU Delft, 2002); Pierrick Maire, "Étude multidisciplinaire d'un développement durable du sous-sol urbain. Aspects socio-économiques, juridiques et de politique urbaine" (Doctoral Dissertation, Swiss Federal Institute of Technology Lausanne (EPFL), 2011).

10 Grégoire Chelkoff and Jean-Paul Thibaud, "Ambiances sous la ville: une approche écologique des espaces publics souterrains" (Grenoble: CRESSON, September 1997).

11 von Meiss, "Entre le dessus et le dessous"; Durmisevic, "Perception Aspects in Underground Spaces Using Intelligent Knowledge Modeling"; Maire, "Étude multidisciplinaire d'un développement durable du sous-sol urbain. Aspects socio-économiques, juridiques et de politique urbaine."

12 "Ambiances sous la ville."

is experienced to varying degrees and is relative to the space one has come from and the anticipation of the space to which one is going.

2.1.1. Pervasive centrality: Encounter and avoidance at multiple scales

Underground spaces establish potential sequences of movement by relating underground activities to each other and to those on the surface. Such spatial networks can be considered as armature-enclave configurations. Bill Hillier and his team have worked since the 1980s on developing a methodology for evaluating spatial configurations metrically and topologically in terms of visible area (two-dimensional isovists) and unobstructed linear armatures.[13] They are interested in how space is conditioned by (and also conditions) 'to-movement' (the destination potential or capacity as an enclave) and 'through-movement' (its path potential or capacity as an armature). Researchers have applied this methodology to underground and multi-level urban spaces and found, for instance, that more visible places are easier to find and tend in commercial contexts to do better economically.[14]

The centrality of a location depends not only on the scale and logic of movement in space, but also on its capacity to be a center at multiple radii, from the 'local' to 'global' scale. Hillier refers to this latter property as 'pervasive centrality,' which posits that if every starting point is a center, then as distance increases from that point, the centrality of each point contained within that particular radius has the potential to increase or decrease. The expansion of centrality out from a single point occurs both convexly (as an enclave or to-movement vector) and linearly (as an armature or through-movement vector).[15] This property of human settlement patterns is evident in the organization of commercial activities. When comparing two shopping malls in the United States, Brown finds that a layout of stores creating many local, but disconnected centers tends to have a negative impact on store occupancy.[16] In their study of two London multi-level mixed use complexes and their surrounding areas, Chang and Penn remark that measuring centrality at the scale of the whole network tends to obscure the impact of local spatial configuration on the distribution of pedestrians.[17] Zacharias observed in his study of a portion of the Montreal Indoor City that the distribution of pedestrians indoors varies more than outdoors and that the

[13] Bill Hillier, *Space Is the Machine: A Configurational Theory of Architecture*, Electronic Edition (1996; repr., Cambridge: Cambridge University Press, 2007); Bill Hillier and Julienne Hanson, *The Social Logic of Space* (Cambridge: Cambridge University Press, 1984).

[14] for wayfinding, see Christoph Hölscher, Martin Brösamle, and Georg Vrachliotis, "Challenges in Multilevel Wayfinding: A Case Study with the Space Syntax Technique," *Environment and Planning B: Planning and Design* 39, no. 1 (2012): 63–82; for the economic success of commercial spaces, see Gordon Brown, "Design and Value: Spatial Form and the Economic Failure of a Mall," *Journal of Real Estate Research* 17, no. 2 (1999): 189–225.

[15] Bill Hillier, "Spatial Sustainability in Cities: Organic Patterns and Sustainable Forms," in *Proceedings of the Seventh International Space Syntax Symposium*, ed. D. Koch, L. Marcus, and J. Steen (Stockholm: Royal Institute or Technology, 2009), K01.1–K01.20.

[16] Brown, "Design and Value."

[17] D Chang and A Penn, "Integrated Multilevel Circulation in Dense Urban Areas: The Effect of Multiple Interacting Constraints on the Use of Complex Urban Areas," *Environment and Planning B: Planning and Design* 25, no. 4 (1998): 507–38.

centrality of corridor segments is a weak descriptor of pedestrian distribution.[18]

On the one hand, the weakness of correlation between the centrality of the streets and corridors and the presence of pedestrians may be due to the failure of the studies to account for pervasive centrality. Zacharias's study measures the centrality of corridor segments in the whole spatial network, while in a later study he confirms that most trips in the indoor city vary between 100 and 300 meters.[19] On the other, the distribution of activities influences the quality of segments as attractors. In their study of the impact of the centrality of the street network on the distribution of land uses, Ozbil and colleagues conclude that the local distribution of pedestrians correlates well with the distribution of land uses on the street network, not only with the degree of centrality of the street segments.[20] Furthermore, the same study finds that the straightness of connections is as important, if not more so, than the density of connections. Analyzing spatial configuration has to address not only centrality that changes at different scales, but also the quality of the connection. A location may be central, but not only to one single characteristic or activity in the built environment. The way the connection is modeled can also differ. Two different forms of centrality at the same scale may tell a different story.

The consequence of pervasive centrality as a structural characteristic of a spatial network is that a general description of spatial configuration must try to account for the nesting of centrality. Encounter and avoidance are not expressed at only one particular metric, but occur pervasively and heterogeneously throughout the urban form. Like many previous studies, this chapter examines the relationship between spatial configuration and a particular urban phenomenon (rents per square meter, see Section 2.7). However, prior to such an investigation, a description of the spatial structure is required that allows configurational categories to emerge from measures of the urban form, rather than from *only* a priori decisions based on hypotheses or existing scientific evidence. As mentioned in section 1.4 of Chapter 1, *a priori* categorizations of urban form err on the side of Platonic abstract universals, where examining the urban form as mass in a particular situation such as Montreal would seek to identify configurational categories as embedded within the

[18] John Zacharias, "Modeling Pedestrian Dynamics in Montreal's Underground City," *Journal of Transportation Engineering* 126, no. 5 (September 2000): 405–12.

[19] John Zacharias, "Underground Pedestrian Trips—trip Generation, Spatial Distribution and Activities in the Montréal Underground," *Tunnelling and Underground Space Technology* 46 (February 2015): 46–51.

[20] However, the street network still remains more significant at larger metrics, see Ayse Ozbil, John Peponis, and Miles Keeping, "Understanding the Link between Street Connectivity, Land Use and Pedestrian Flows," *URBAN DESIGN International* 16, no. 2 (March 16, 2011): 125–41.

mass and to tease them out through a process of deciphering—identifying concrete universals.[21]

2.1.2. The adequacy of regression analyses for spatial phenomena: From empirical adequacy to experimental production and control

Once configurational categories have been identified within the urban form, they may have a measurable impact on spatially distributed urban phenomena. Most studies establish this relationship statistically using bivariate correlations (a linear comparison of the distribution of the phenomenon of interest and a spatial metric) or either univariate or multivariate linear regressions (a linear fit of one or several spatial metrics to the spatial phenomenon). Zacharias's study seeking to quantify the relationship between average number of pedestrians per axial line and their centrality (as *closeness*, or the inverse of distance) uses bivariate correlations.[22] A study conducted in Bologna examines the distribution of retail locations and the centrality of street segments using bivariate correlations.[23] Chang and Penn's study of indoor shopping complexes in London uses bivariate linear regressions of pedestrian counts per axial line and the measure of centrality of the lines.[24] Ozbil and colleagues examine different spatial metrics in separate multivariate regressions models in looking at the impact of centrality on the distribution of land uses.[25] These studies, however, do not account for spatial interactions—that is, the fact that a clustering of pedestrians or land uses in one location may be affected by the presence or absence (encounter or avoidance) of clusters in neighboring locations.[26] Spatial interaction requires more sophisticated forms of regression analysis, which are typically adopted by spatial econometrics.[27]

Compounding the problem of methodological and statistical adequacy is a philosophical one posed by the use of statistical regressions for identifying universal laws that can be represented mathematically and that are generalizable outside the sample in which they are observed. In the use of the regression in scientific inquiry, there is often a disconnect between the way in which the regression is carried out and interpreted and the way in which the experimental setup is diagnosed and evaluated. As Amit Ron observes, few researchers would argue that the resulting regression equation would have a one-to-one relationship with the social phenomenon of investigation. However, the diagnosis and discussion of the results

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21 for an in depth discussion of this, see Vahid Moosavi, "Pre-Specific Modeling: Computational Machines in a Coexistence with Concrete Universals and Data Streams," in *Metalithikum IV, Coding as Literacy*, ed. Vera Bühlmann, Ludger Hovestadt, and Vahid Moosavi (Vienna: Birkhäuser, 2015), 132–66.

22 Zacharias, "Modeling Pedestrian Dynamics in Montreal's Underground City."

23 Sergio Porta et al., "Street Centrality and Densities of Retail and Services in Bologna, Italy," *Environment and Planning B: Planning and Design* 36, no. 3 (2009): 450–65.

24 Chang and Penn, "Integrated Multilevel Circulation in Dense Urban Areas."

25 Ozbil, Peponis, and Keeping, "Understanding the Link between Street Connectivity, Land Use and Pedestrian Flows."

26 This is a common problem in spatial configurational studies, see Andres Sevtsuk, "Path and Place: A Study of Urban Geometry and Retail Activity in Cambridge and Somerville, MA" (Doctoral Dissertation, Massachusetts Institute of Technology, Dept of Urban Studies and Planning, 2010), section 3.4.

27 Luc Anselin, *Spatial Econometrics: Methods and Models*, Studies in Operational Regional Science 4 (Dordrecht: Kluwer Academic Publishers, 1988).

of the regression model often suggest that the researcher believes that such a one-to-one correspondence is achievable and has failed due to empirical inadequacy. Such a failure is explained as due to problems in theory, to missing data or to the invalidity or inadequacy of tests of statistical validity.[28]

For instance, Zacharias accounts for the weak performance of his regression model in predicting pedestrian distributions in the Montreal underground by resorting to an argument for more data. In an effort to predict pedestrian volumes in multi-level spaces, Chang and Peng explain discrepancies in the results of their regression model as resulting from the need for additional observations. Both studies rely on what Ron refers to as an empiricist approach to scientific practice, which addresses phenomena as closed systems governed by universal laws. As an alternative, Ron proposes a critical realist approach, which addresses the regression equation as a model that helps to reveal an underlying mechanism generating the data. Rather than being governed by universal laws, the mechanism reproduced by the model exposes certain locally contingent regularities or law-like tendencies. The outcome would therefore not be a universal law, because the equation represents a contingent distribution of agency and internal relations of causality. Rather, it is the relations themselves, as tendencies or regularities, which may have a certain universality if they appear similarly either in other contexts, or in the future in the same context.[29]

As such, the inadequacy that Zacharias and Chang and Peng observe in their models is less a problem of empirical adequacy than of experimental production and experimental control. Experimental production is that which "triggers the mechanism that causes the thing [the particular spatial phenomenon] to operate."[30] While the regression analysis cannot actively trigger the mechanism (but approaches it through collected data), this is not the case for experimental control, which is the attempt "to prevent any interference with the mechanism and thus make the action observed."[31] When that mechanism is distributed over space, the experimental control necessary for regression model requires greater sophistication to be able to control for spatial heterogeneity.[32] Martins argues that the use of regressions in economics (econometrics) tends to engage with regression equations as models of closed systems (of exogenous relations), which (from the same critical realist view adopted by Amit Ron) presumes to identify universal laws.[33] I would argue, however, that spatial econometrics does more to respect the

28 Amit Ron, "Regression Analysis and the Philosophy of Social Science: A Critical Realist View," *Journal of Critical Realism* 1, no. 1 (July 15, 2002): 119–42.

29 Ibid.

30 Ibid., 136.

31 Ibid., 137.

32 Anselin, *Spatial Econometrics*.

33 Nuno Ornelas Martins, "Critical Realism, Econometrics and Heterodox Economics," in *Handbook of Research Methods and Applications in Heterodox Economics*, by Frederic Lee and Bruce Cronin (Cheltenham, UK: Edward Elgar Publishing, 2016), 222–36, http://www.elgaronline.com/view/9781782548454.xml.

Data	Source	Format	Initial Transformations
Pedestrian network of Indoor City	Observatory of the Indoor City (OVI)	Polygon and line shapefiles	None
Rental Roll (2004) (n=3879, from 18,682)	OVI (orig. Montreal GIS)	Polygon shapefile	Removal of spaces outside the Indoor City or the pedestrian network.
Layout of indoor locations (n=768, from orig. 849)	OVI	Polygon shapefile	Removal of spaces that were closets/toilets or that could not be matched with the Rental Roll.
Property Roll (2004) (n=8331, from orig. 18,056)	OVI (orig. Montreal GIS)	Polygon shapefile	Collapse properties on same parcel to calculate overall density of commercial activities.
Street network with addresses	Adresses Québec[1]	Line shapefile	Conversion to geolocator in ArcGIS to geolocate Rental Roll approximate entry points
Parks (n=16, total area of 95,668 m^2)	OVI (orig. Montreal GIS)[2]	Polygon shapefile	None
Building footprints (2004)	OVI (orig. Mtl GIS)	Polygon shapefile	None
Tree canopy of Ville-Marie (from 2007 satellite photo) (total area = 1,941,692 m^2)	Portail de données ouvertes de Montréal[3]	Polygon shapefile	Conversion to point data in order to snap canopy area to a nearest network segment.
Outdoor pedestrian counts (n=1,567,781 total average pedestrians per weekday in 2009)	Portail de données ouvertes de Montréal	Point shapefile	Street corner counts were aggregated into a single point and totalled over a whole day.

Table 2.1. Data sources and transformations

1. addressesquebec.gouv.qc.ca
2. www.observatoiredelavilleinterieure.ca
3. donnees.ville.montreal.qc.ca

endogeneity of spatial relations, not only of that which is accounted for as contributing to the spatial mechanism (the explanatory variables), but also of that which has been omitted (as a spatially lagged error term).

2.1.3. Methodological design and position: Scientific rigor without overdetermination or abstract universals

In the use of spatial econometrics in evaluating spatial configuration with regression analysis, the study carried out in this chapter borrows in methodological design from research carried out by Andres Sevtsuk in the Cambridge and Somerville neighborhoods of Boston in the late 2000s.[34] This is the only study, to my knowledge, to combine spatial configurational analysis and spatial econometric regressions. Sevtsuk's statistical model seeks to measure the probability that a building will house a food or retail activity, and the contribution made by the geometry of the built environment to increasing or decreasing that probability. In his argument for spatial econometric methods, Sevtsuk claims that "studies of urban form using different graph theory metrics have habitually been conducted in an ad-hoc manner, ranking different measures of urban form against an outcome of interest, without clear hypotheses, behavioral basis, or an economic foundation."[35] I agree with his estimation that the statistical methods in previous

34 Sevtsuk, "Path and Place: A Study of Urban Geometry and Retail Activity in Cambridge and Somerville, MA."

35 Ibid., 62.

configurational studies merit a more rigorous methodological approach—a concern of experimental control. However, I would argue that, in building a model of a spatial mechanism, hypotheses should not serve to overly determine the form of the model, nor opt unconditionally for certain categories of distinction borrowed from theory or previous research. Because this dissertation takes a critical stance towards Platonic abstract universals, the categories used to describe spatial configurations will be identified in the dataset, entailing a significant change in the conditions of the experimental production and likely a distancing from more orthodox research designs in spatial econometrics.

The methodological design questions certain hypotheses while considering others as givens. It investigates the hypothesis that the presence of heterotopiality of a multi-level spatial network can be understood through differences in spatial configuration and that this configuration has an impact on the economic value of spaces in the network. The importance of pervasive centrality in understanding spatial phenomena, as evidenced in the literature, means taking as a given the hypothesis that configuration cannot be understood merely through single metrics but that they must be captured together. The theoretical framework presented in Chapter 1 requires also taking as a given the hypothesis that the categories of pervasive centrality must be addressed as already embedded within the existing urban fabric—as concrete universals 'hidden' in the spatial model.

The following sections will then first present the spatial network model, then some basic descriptive statistics of individual spatial metrics before exploring a strategy to capture pervasive centrality. Then the new spatial configurational categories will be examined and placed, along with some other descriptive criteria into a spatial econometric model in order to test their significance in describing the variation of rental values in the Montreal downtown, including the Indoor City and surrounding context together. After exploring the results of this analysis in detail in the global model, an additional analysis using geographically-weighted regression will explore the spatial distribution of the impact and statistical significance of the configurational categories on rents per square meter. The conclusion will summarize the results and examine anew certain observations made by previous research.

2.2. Building a model: Data and transformations

In order to evaluate spatial configurational characteristics of the Montreal downtown, a three-dimensional spatial model was built in ArcGIS using data from several sources (Table 2.1). The Observatory of the Indoor City, based at the University of Montréal, provided the plans in GIS format for the interior and underground pedestrian corridors as well as the layouts of several of the commercial centers and the Rental Roll (*rôle locatif*), which contains the rent paid by each tenant in the downtown as of the last (and final) data collection in 2004.[36] Although a total of 18,682 spaces are contained in the Rental Roll, only spaces that are directly connected to indoor or outdoor pedestrian paths were included in the model, reducing the sample to 3879 (Figure 2.1). These locations were geocoded using an address locator built with data from the *Adresses Québec* database. Where it was known that the address was identifying a location situated indoors, the entry point was placed at an approximate center point of the parcel snapped to the interior corridor (Figure 2.2). The Observatory also provided the 2004 layouts of the indoor locations, meaning that, for 768 of them, it was possible to both situate their entries more accurately and match them to the Rental Roll database, which also included the classification category indicating activity type.[37]

Additional data were included in the model in order to calculate centrality to other characteristics of the built environment (Figure 2.2). The location of parks was already part of the database provided by the Observatory. There are 16 parks in the study area with a total of 95,668 square meters (a portion of the expansive Mont-Royal Park is included in this). As a complement and to capture small park-like or green spaces, tree canopy data calculated in 2007 from satellite photos was downloaded for free from the Montreal Open Data Portal. Pedestrian count data at street intersections from 2009, also available from the Open Data Portal, was transformed into a single average count for weekdays. This information was of interest for the study, because the centrality to a park or housing can be interpreted as either encounter or avoidance, which can have an impact on rental values. Although the study area is composed of mostly food and retail, office and cultural spaces, the OVI's Property Roll data from 2004 included the number of housing units in each property and these were used as a proxy for residential population.[38] The data is of course not perfect. It comes from different sources collected at different times. Most significantly, pedestrian counts were not available for the Indoor City and those collected in 2009 may reflect the changes undergone by the *Place des Arts* between 2004 and 2009. However, the overall movement network and the distribution of activities does not appear to have changed significantly over this time period.

A representation of the pedestrian network was built using the Depthmap algorithm[39] run on a plan of each level of the downtown contained in the model in which any barriers to movement were drawn as polygons. The algorithm produced an axial map that drew

36 Martin Gagnon and Sylvain Garcia, "Le Système d'information à référence spatiale (SIRS)" (Montréal, Canada: Université de Montréal, March 2005), www.observatoiredelavilleinterieure.ca.

37 As part of the Codes d'utilisations des biens fonds maintained by the Affaires municipales et Occupation territoriale : http://www.mamrot.gouv.qc.ca/evaluation-fonciere/manuel-devaluation-fonciere-du-quebec/codes-dutilisation-des-biens-fonds/

38 The OVI database also had the Property Roll from 2007, which helped complete or verify information that was missing in 2004 for a property that was nevertheless marked as having been in Montreal since 2004 or before.

39 Alasdair Turner, Alan Penn, and Bill Hillier, "An Algorithmic Definition of the Axial Map," *Environment and Planning B: Planning and Design* 32, no. 3 (2005): 425–44.

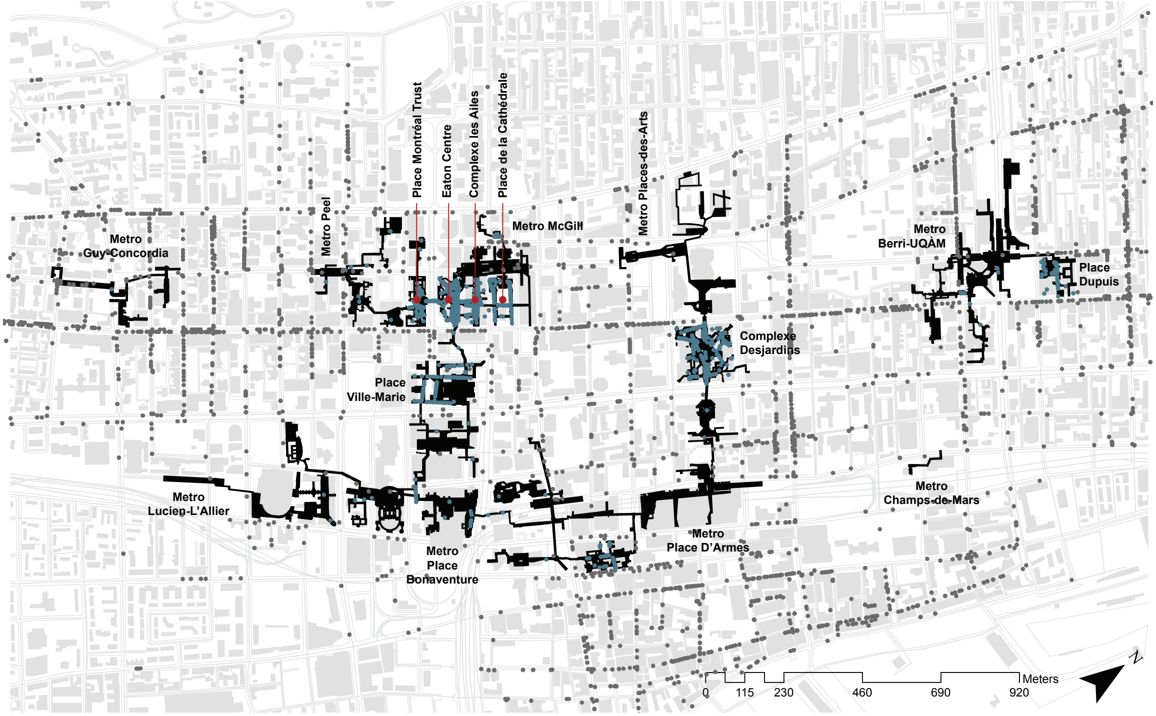


Figure 2.1. Study area with analysis points and indoor city and street network.

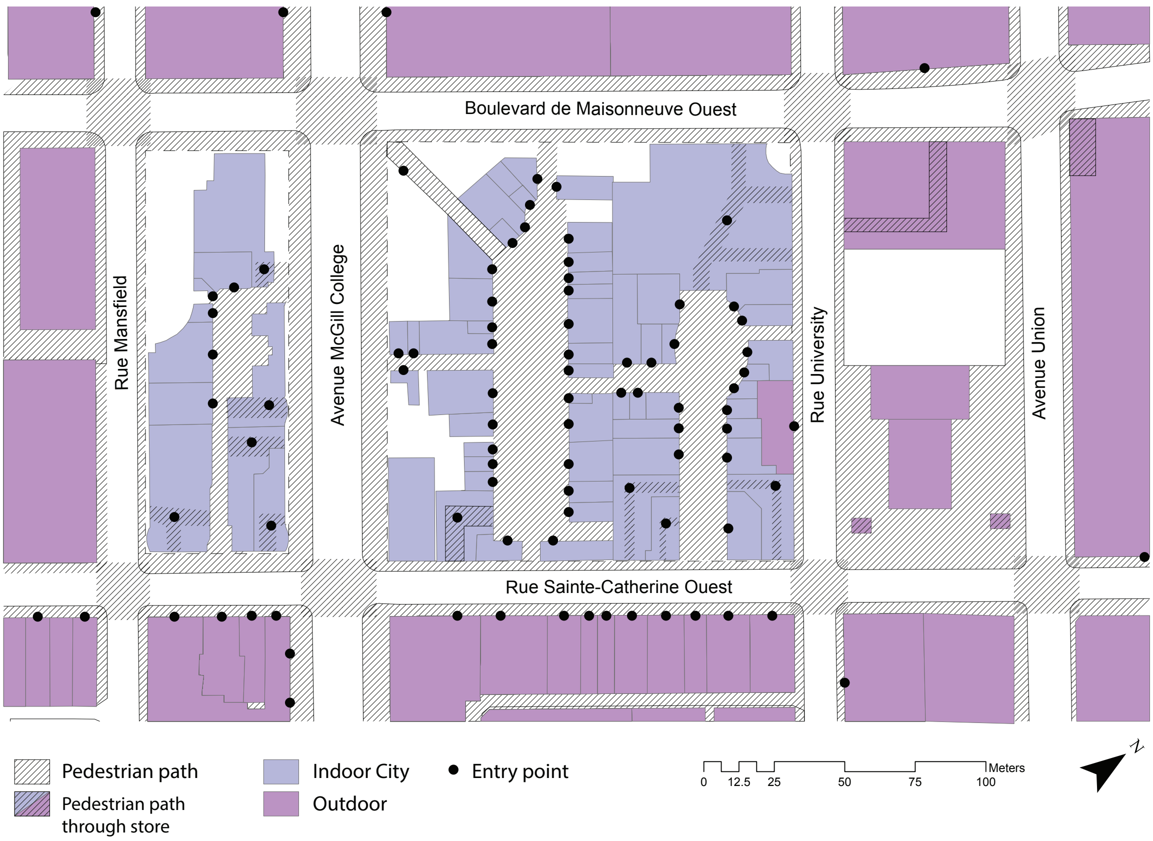


Figure 2.2. Diagram explaining the model through the example of the ground floor levels of Place Montréal Trust (between Mansfield and McGill College) and Eaton Centre and Complexe Les Ailes (between McGill College and University).

shortest paths through all convex spaces. This allowed the model to avoid restricting movement to street centerlines or sidewalks and to differentiate between streets that could be crossed anywhere and those where crossing could only practically occur at intersections and pedestrian crosswalks (this was developed using Google Streetview and the author's personal knowledge of the Montreal downtown). Vertical connections between floors were represented as vertical lines at the approximate locations of elevators, stairs and escalators. The placement of indoor connections and corridors was verified by the author during a two-week visit to Montreal in June 2014. The model was refined by hand in Autodesk AutoCAD, imported into ArcGIS and converted to a Network Dataset. Additional characteristics were calculated, including the distance and number of turns to the nearest metro station, the potential visibility of the store entry (a 2D isovist calculated by DepthMap) and the density of commercial activities on the parcel (to account for the draw that food and retail activities on other floors may have).

2.3. Descriptive statistics

Descriptive statistics of the metrics examined already reveal some overall differences between food and retail spaces indoors (n=322) and outdoors (n=1209). Looking at the surface area of locations, indoor locations are on average smaller (Figure 2.3). A hotspot analysis conducted in ArcGIS revealed that the size of retail locations tends to be distributed evenly and that they are not highly spatially autocorrelated (or clustered). Indoor locations have an average rent that is more than twice the rent per square meter of outdoor commercial areas, which suggests additional costs related to being part of a privately managed commercial space. As commercial spaces in the indoors may benefit from clientele arriving from or going to metro stations, the metric and topological distances, in meters and turns respectively, were calculated from each food and retail location. Indoor locations unsurprisingly tend to be closer, but on average not by that much (429 m outdoors compared to 326 m indoors), to metro locations, but tend to require an additional turn to get there (Table 2.2). This may reflect the circuitous paths often required to move between floors. The visible area from the location entry emphasizes the difference in being indoors or outdoors. Indoor locations are less visible from a larger area than outdoor locations. Visibility tends to be greater around street intersections, such as Amherst, St-Denis and St-Laurent along Sainte-Catherine and around parks and squares like Dorchester, Place du Canada, Place des Festivals, Quartier des spectacles, and the Émilie-Gamelin and Viger Parks (Figure 2.4). Although increased visibility may be advantageous, the intensity of visible encounter organized by indoor spatial configurations concentrates the visual field to ensure that a store front cannot be 'missed.' Whether this particular way of articulating encounter and avoidance is characteristic of

	Mean Outdoor (Indoor)	Minimum Outdoor (Indoor)	Maximum Outdoor (Indoor)
Surface Area (m^2)	672.75 (306.72)	5.57 (5.57)	63,610.59 (21,782.59)
Value per m^2 ($CDN)	230.42 (711.05)	46.44 (89.26)	1599.68 (1614.59)
Distance to nearest metro (m)	428.70 (325.91)	58.22 (39.62)	936.24 (574.05)
Turns to metro (>20°)	6.28 (7.62)	2 (0)	11 (13)
Area visible from entry (m^2)	2893 (22,399)	1100 (35)	105,766 (20,480)

Table 2.2. Descriptive statistics of non-connectivity metrics (outdoor: n=1209; indoor: n=322)

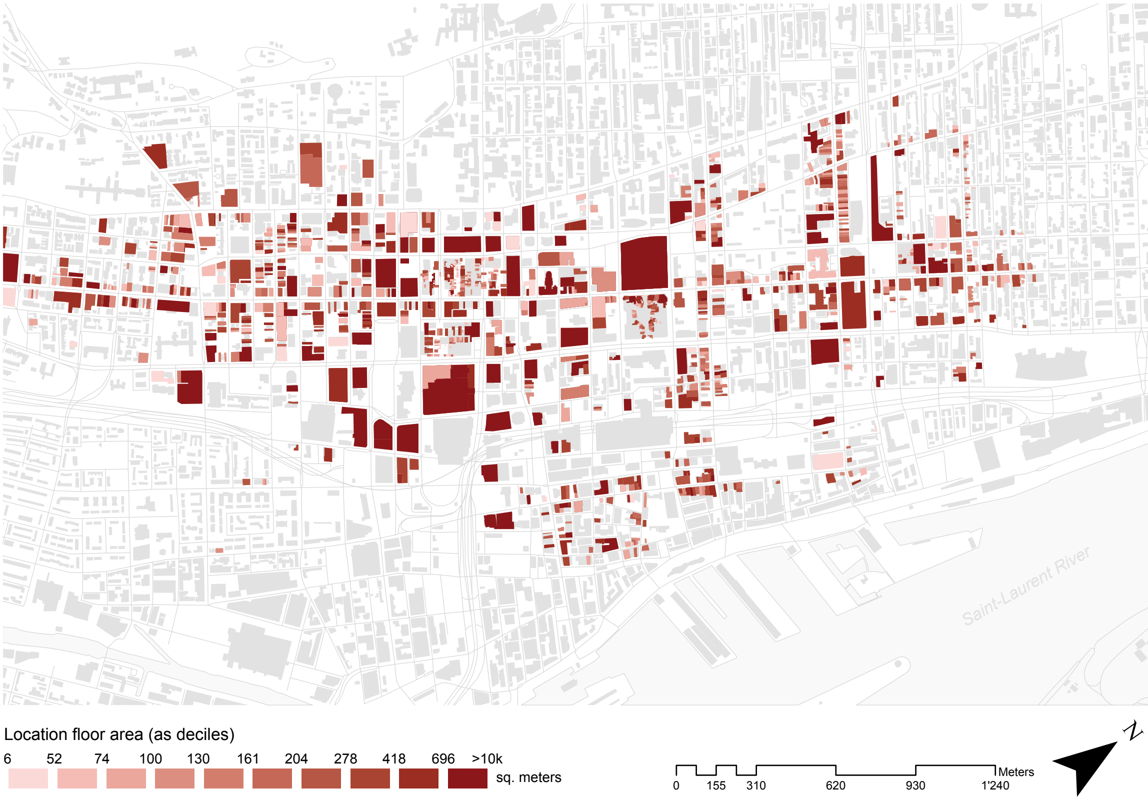


Figure 2.3. Floor area classed according to decile. The size of stores is spatially well-distributed.

indoor spaces (and constitutive of a sort of heterotopiality) will be investigated below.

2.4 Calculating connectivity: Examining configuration

Accessibility metrics were calculated for each location on the network using the Urban Network Analysis (UNA) Toolbox plugin for ArcGIS.[40] As opposed to other configurational studies of multilevel indoor and underground spaces, the toolbox allowed calculations to be performed using the location entry points and to weight them according to their floor area. Rather than choose one particular accessibility metric (and therefore a particular model, or abstract universal, of how pedestrians make path decisions) or a distance at which most trips occur, gravity, straightness, betweenness and turns

[40] http://cityform.mit.edu/projects/urban-network-analysis.html

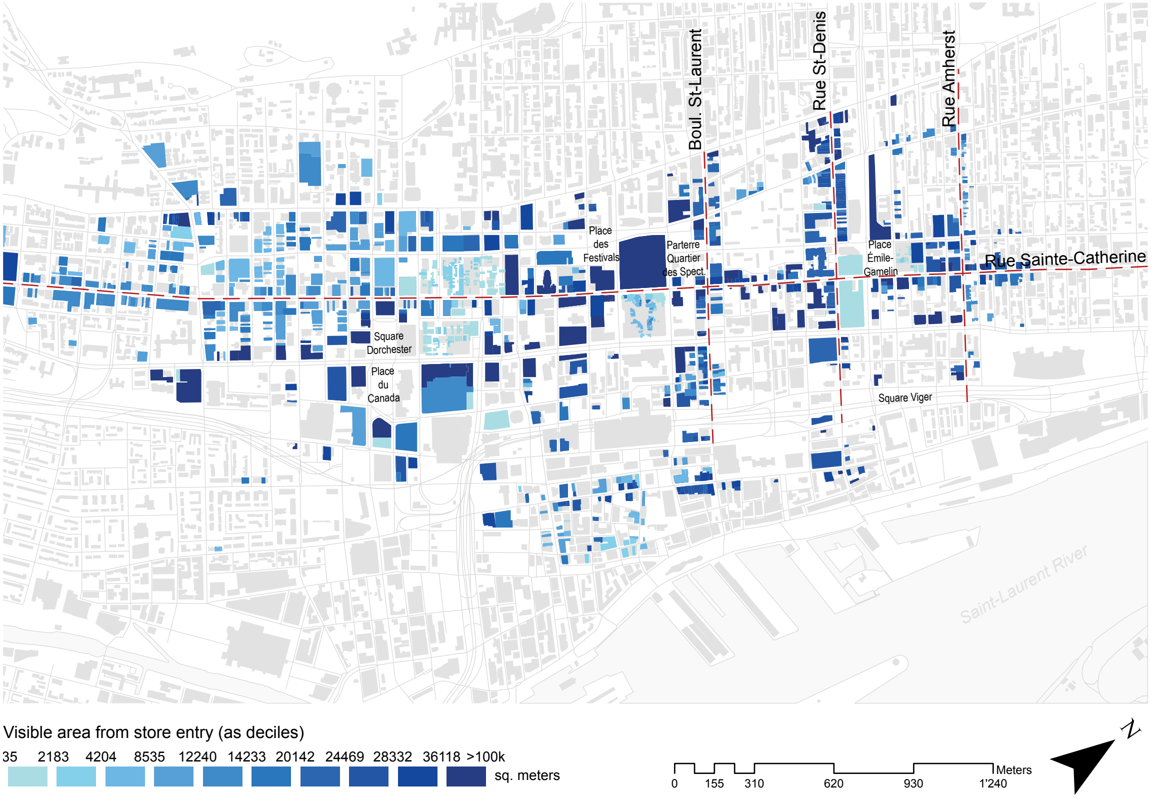


Figure 2.4. Viewable area in front of store (proxy for visibility) as deciles. Storefronts have a higher visibility at intersections and around park or open areas, where they would theoretically be seen from further away.

metrics were run at 100 to 1600 meter distances on the network.[41] As it is only initially a question of configurational differences between the Indoor City and the surrounding urban fabric, but also later the contribution of these differences to the economic success of retail locations in particular, the sample discussed here is only retail locations for which rental value was available, a total of 1541 locations.[42] Locations were therefore weighted according to the surface area dedicated to food or retail activities, in order to examine the configurational relationships of one particular activity. Because there may be a different relationship between a food or retail location and other locations, depending on whether they are indoors or outdoors, access to only indoor and only outdoor commercial area was calculated *separately*. Other weights evaluated characteristics that food and retail locations might want to encounter or avoid, such as the number of housing units, the amount of green space (as tree canopy and public parks) and the number of pedestrians circulating outside at a 400-meter radius (Figure 2.5). However, betweenness metrics were not calculated for housing units, park space and area of tree canopy, as it is not likely that they constitute many origin destination pairs (park-to-park, housing unit-to-housing unit, treed area-to-treed area.

[41] Gravity was preferred to closeness and reach because it includes a distance decay, thereby giving greater weight to closer locations. The decay adopted the pedestrian distance decay proposed by Handy and Niemeyer "Measuring Accessibility: An Exploration of Issues and Alternatives," *Environment and Planning A* 29, no. 7 (1997): 1175–94, who claim from empirical evidence that the distance threshold of most pedestrian trips is about 800 meters, or a ten-minute walk. This is a sort of abstract universal.

[42] The regression analysis is limited to those food and retail locations with a rent value (the dependent variable), a reduced sample of 1541 locations. Accessibility metrics were calculated using a larger sample of 2083 locations.

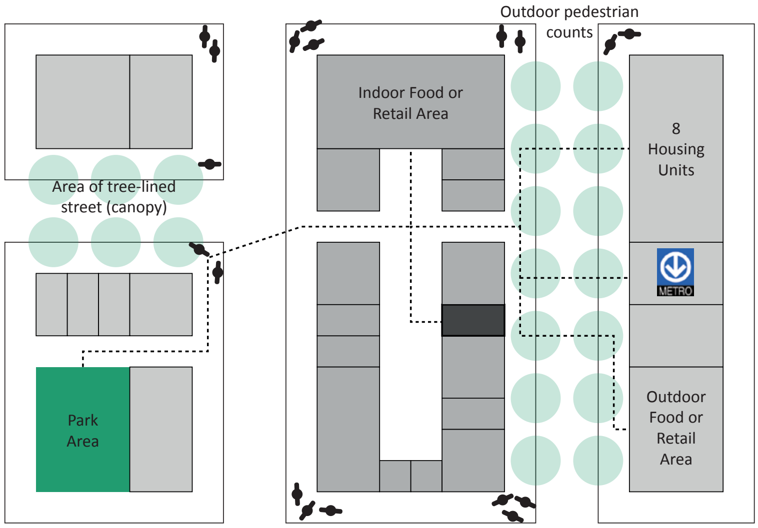


Figure 2.5. Illustration of the spatial network relationships calculated between each food and retail location and all others at different metric or topological distances.

Some general observations can be made about the degrees of centrality of locations at different radii. On average, indoor stores have nearly twice as much commercial space within 100 meters than outdoor spaces and this appears to be the case all the way to 1600 meters (Table 2.3). At 400 meters, the accessible area is highest on the street blocks around Eaton Centre to Place Ville-Marie and the central train station and the lowest values are situated east of St-Laurent and west of Rue Guy (Figure 2.6). If accessibility is considered as straightest paths (where the pedestrian would avoid major changes in direction), indoor accessibility is still greater than for outdoor locations at low radii, but appears to decrease at larger radii (where overall paths tend to resemble straight lines anyways). At 800 meters, the highest values (in top percentiles) are located between Rue Crescent and Rue St-Urbain (Figure 2.7), which is not surprising as this is a large part of the central business district. Neighborhoods become more residential further east and west.

The betweenness metric calculates all shortest paths to and from origins and destinations (at a particular radius) that pass in front of a location. When weighting locations by surface area, this value can be interpreted by comparing one location to another and be roughly estimated as potential clientele.[43] Betweenness reveals linearity (armature-ness) in the urban fabric. At 800 meters, food and retail locations on Rue Ste-Catherine between Rue de la Montaigne and Rue de Bleury, as well as around the intersections of Ste-Catherine and Rue St-Laurent and north of Ste-Catherine and Rue St-Denis, tend to have access to a larger amount of potential clientele along shortest paths (Figure 2.8). Indoor locations tend to be situated less often along shortest paths. At 800 meters, some of the ground floor locations have betweenness values in the upper percentiles, but they are close to indoor axes, such as the corridor that links Eaton Centre at its first basement level to Place-Ville-Marie and on to the

[43] Unless we interpret surface area to be a proxy with number of clientele, which is probably a stretch. Larger stores do not necessarily have more clients than smaller stores.

	Mean Outdoor (Indoor)	Minimum Outdoor (Indoor)	Maximum Outdoor (Indoor)
Accessible food and retail area			
Gravity 100 m	3931 (9482)	0	54,805 (48,840)
… 1600 m	70,848 (124237)	15,912 (43,629)	161739 (163244)
Straightness 100 m	3907 (7880)	0	59955 (48840)
… 1600 m	303546 (363222)	97,057 (159,878)	468359 (459684)
Betweenness 100 m	15,361 (69,356)	0	379972 (392231)
… 1600 m	14,236165 (8216804)	0	156,493,193 (60,959,373)
Turns 1	109,386 (9115)	3991 (0)	238345 (178123)
… 4	477733 (198656)	418168 (0)	517154
Accessible housing units			
Gravity 400 m	30 (11)	0	69 (50)
Straightness 400 m	36 (14)	0	82 (54)
Accessible park area (m²)			
Gravity 400 m	1420 (2173)	0	16383 (12790)
Straightness 400 m	2029 (3112)	0	22174 (17081)
Accessible tree canopy (m²)			
Gravity 400 m	13,991 (8221)	4063 (693)	36049 (16803)
Straightness 400 m	19696 (11533)	5518 (1007)	50298 (23750)
Accessible outdoor pedestrians			
Gravity 400 m	76,436 (147,856)	5742 (42248)	256637 (244912)
Straightness 400 m	129504 (232928)	8468 (60387)	559410 (446444)
Betweenness 400 m	2,652,198 (2,541,402)	0	79,780,403 (21,241,766)

N.B. Apart from the measures omitted here and indicated above, accessibility to only indoor and only outdoor food and retail area was also calculated to explore marked differences if they were not considered together.

Table 2.3. Descriptive statistics of centrality metrics (outdoor: n=1209; indoor: n=322)

Central Station (where there is a concentration of food and retail).[44] When considering only access to indoor commercial locations, at 400 meters, several centers emerge, particularly along Ste-Catherine between Rue Metcalfe and Rue Aylmer, around the mall complexes bordering Eaton Centre and Place Ville-Marie (Figure 2.9). Other parts of the downtown are not at all likely to have origin-destinations pairs of indoor locations passing in front of them, including (as the bluest) the intersections of Rue Ontario, Rue St-Laurent and Rue St-Denis and further south along St-Laurent to Rue de la Gauchetière. The betweenness measures therefore reveal an axial structuring of encounter and avoidance that implicates both the Indoor City and the surrounding surface food and retail locations. It is interesting to note that there are more outdoor locations that are only one turn (a change of about 20° in direction) away from a food and retail surface area than indoor locations (Table 2.3). This may be due to indoor pedestrian paths tending to be more circuitous, something that may be both heterotopic and constitutive of a particular articulation of encounter and avoidance.

If locations are weighted by other characteristics of the urban area, slightly different patterns emerge. For access to housing units, outdoor locations are more likely, on average, to be passed in front

44 As mentioned previously, while the analysis could account for the total commercial area in the Central Station, the precise location of the stores was not available, but the corridor continues through the station to Place Bonaventure which is at the intersection of east-west corridors.

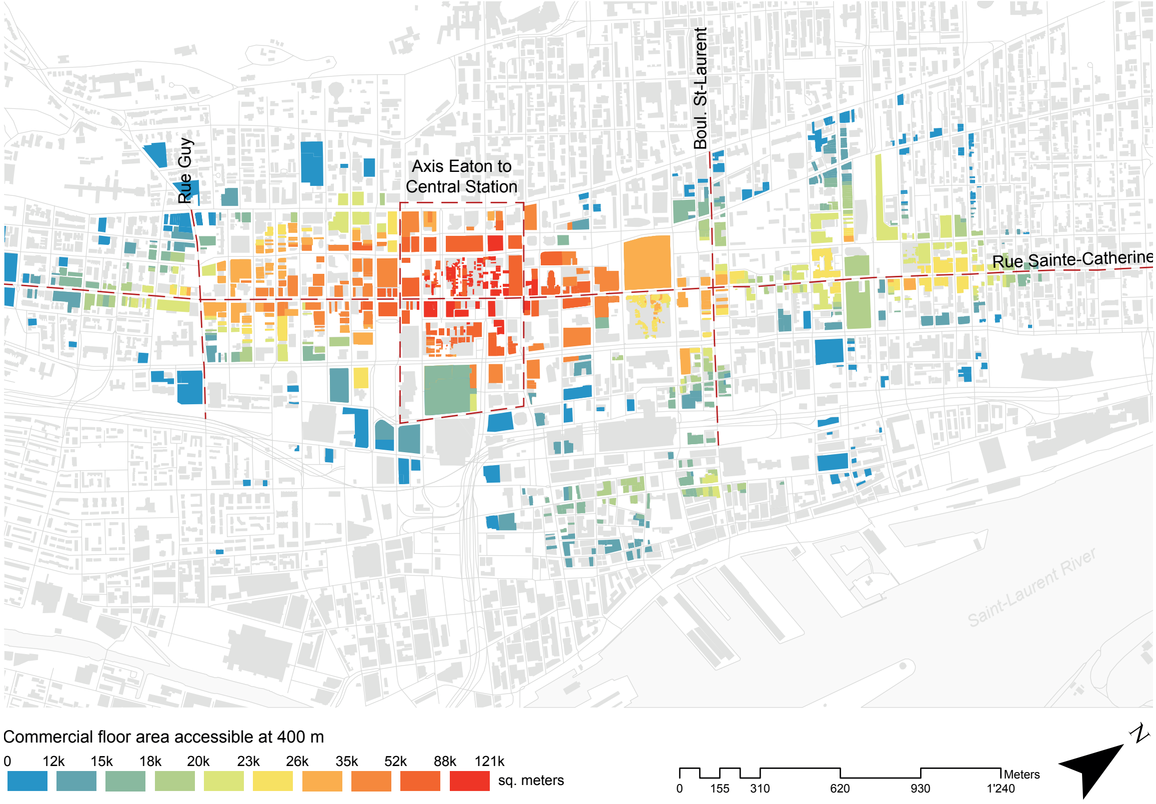
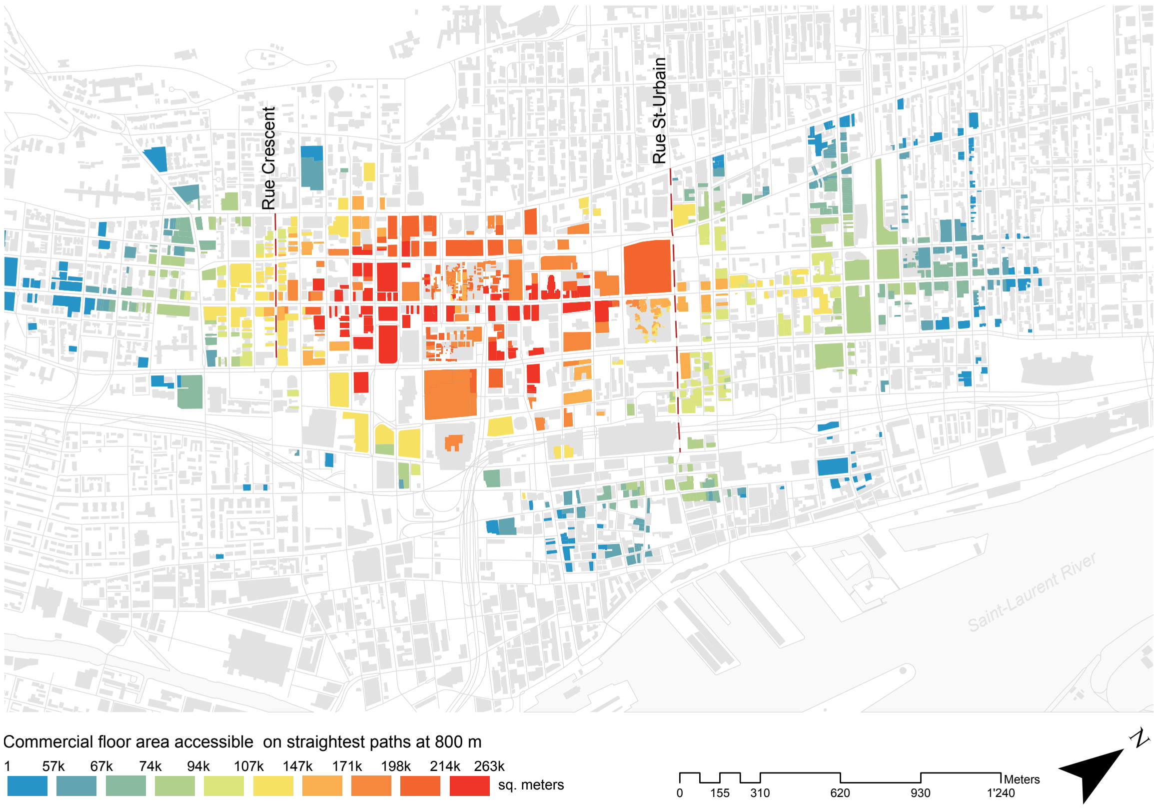


Figure 2.6. Commercial floor area accessible at 400m, with a concentration around the axis from Eaton Centre to the Central Station. ▲

▼ Figure 2.7. Commercial floor area accessible on straightest paths at 800 m, with higher values especially on Rue Sainte-Catherine between Crescent and St-Urbain.



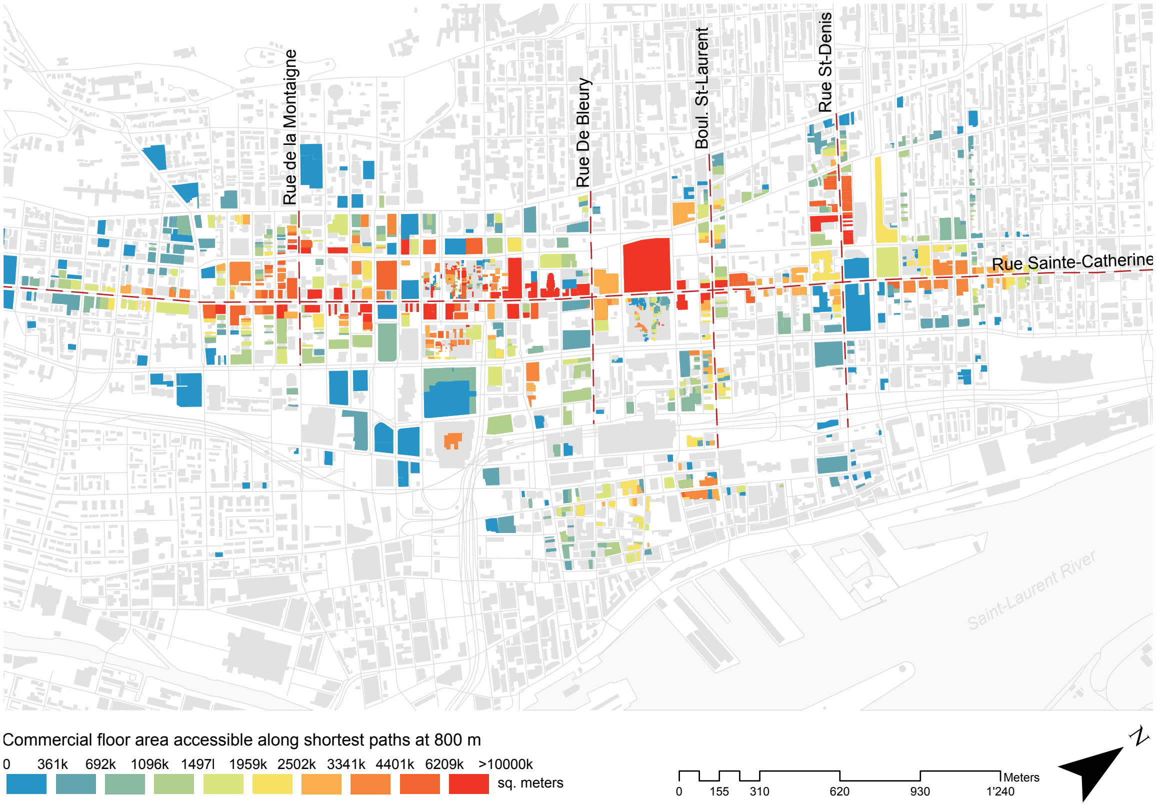
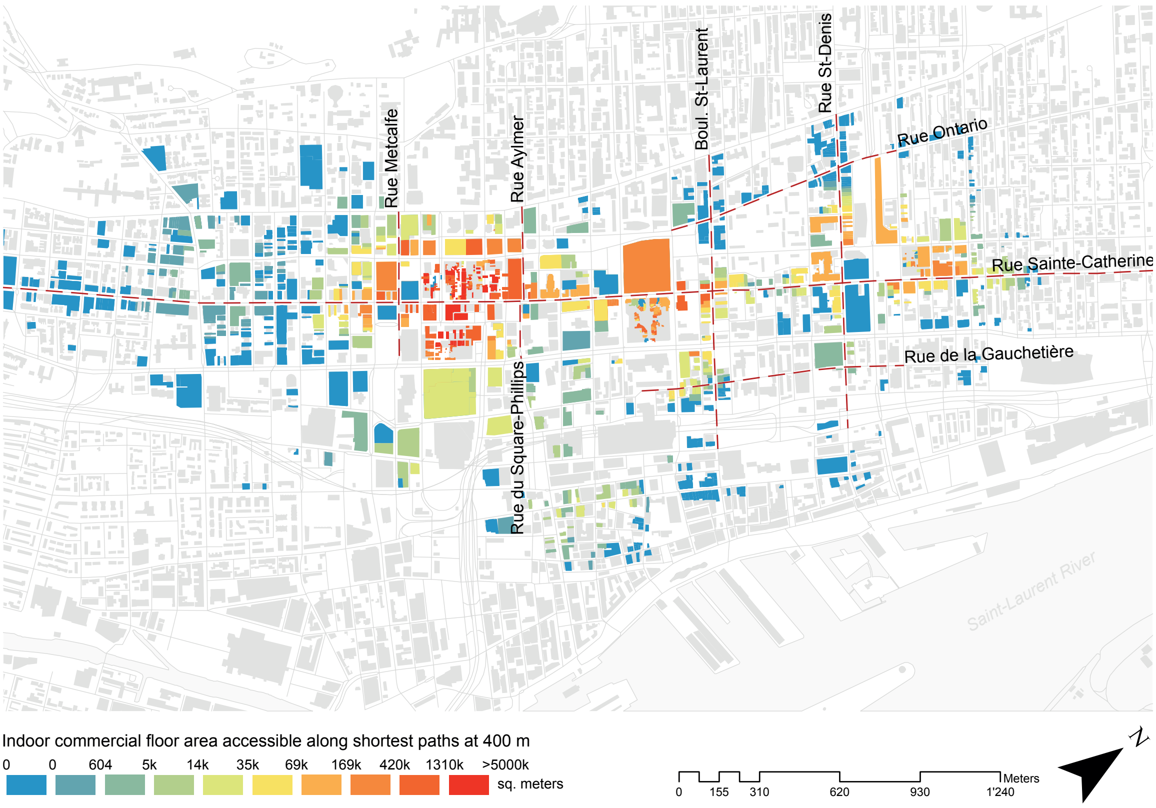


Figure 2.8. Commercial floor area accessible between origin and destination pairs at 800 m ▲

▼ Figure 2.9. Indoor commercial floor area accessible along shortest paths at 400 m



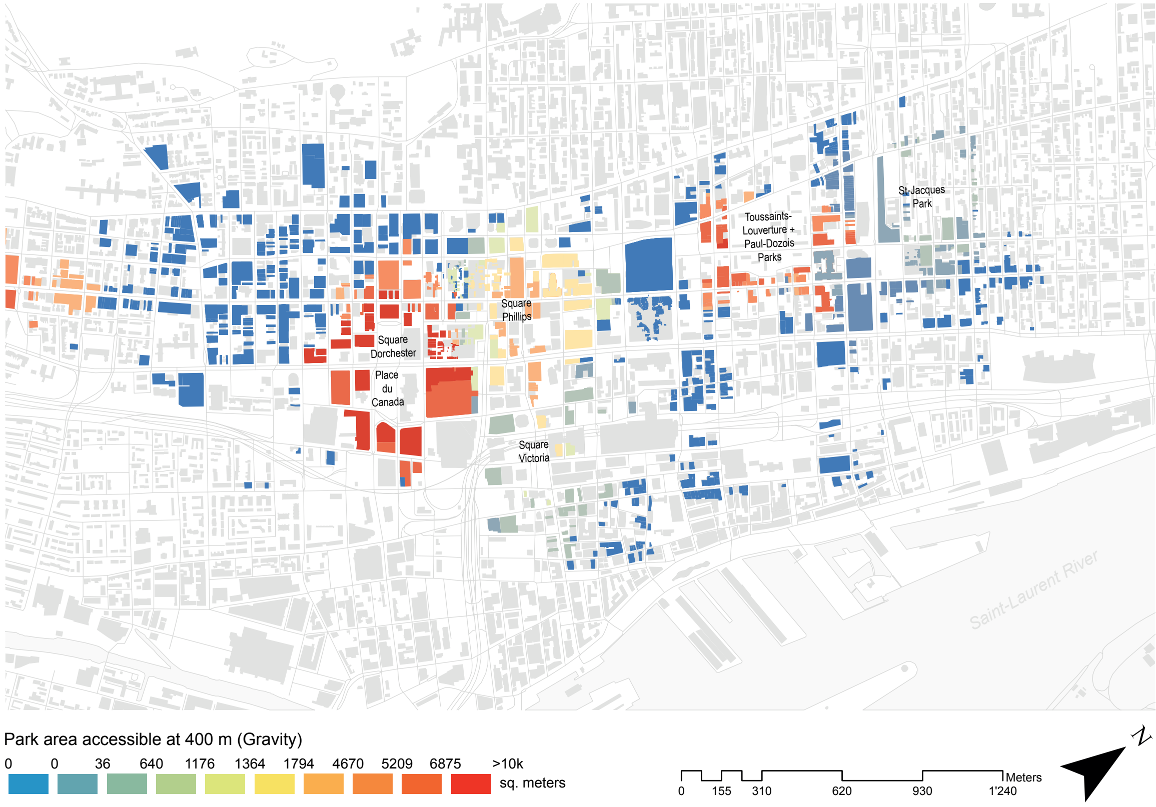
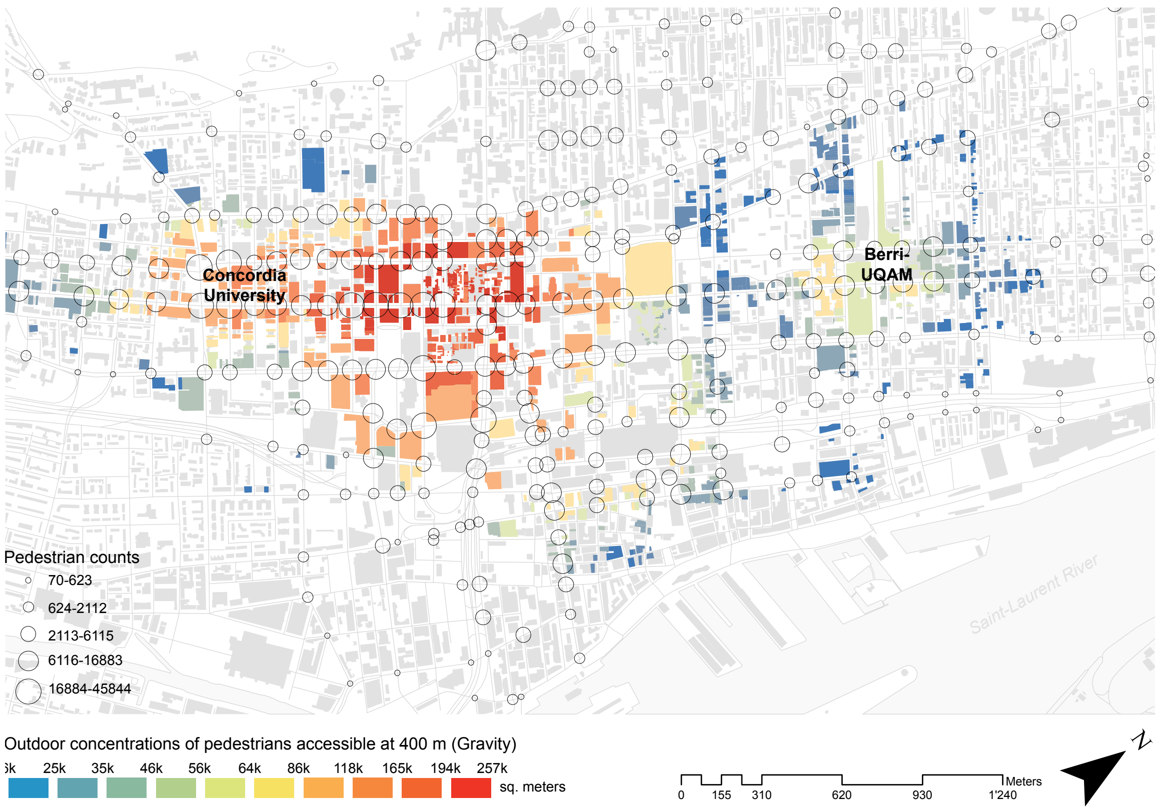


Figure 2.10. Park area accessible at 400 m. ▲

▼Figure 2.11. Outdoor concentrations of pedestrians accessible at 400 m.



of on trips starting and ending at buildings with housing units. As previously shown in Table 2.3, indoor locations tend to be further away from parks. Mapping the analysis at 400 meters shows how accessibility to park area clusters around the largest parks and public places in the study area, from Square Dorchester and Place du Canada to the Toussaint-Louverture and Paul-Dozois Parks situated as part of the Habitations Jeanne-Mance housing complex, situated just between the Place-des-Arts, Complexe Desjardins and Berri-UQAM north-south axes of the Indoor City (Figure 2.10). Parts of the Indoor City are relatively close to parks, for example the western side of Place-Ville Marie which opens on to Square Dorchester. Green spaces are of course not limited to parks, but on average indoor locations access a smaller amount of tree canopy in the study area. This varies around parks, squares and streets that have a larger or small amount of tree-covered area.

Different from the relatively stable distribution of activities, pedestrians cluster either by choice or by necessity in certain parts of the downtown. The 2009 aggregate pedestrian counts (made outdoors only) for an average weekday reveal large concentrations around the commercial area around Eaton Centre to the main station, around Concordia University to the west and the area centered on the University of Quebec in Montreal (UQAM) in the east (Figure 2.11). All three areas are also metro stations, where many people pass each day, even if their final destination is not in one of those locations. Of course, commercial activities condition and are conditioned by these concentrations of potential clientele. The pattern of pedestrians accessible at 400 meters follows a pattern similar to that of access to commercial area at the same network radius, with the Eaton Centre to Central Station axis at the highest, followed by the area around Concordia and then the Berri-UQAM metro station. These metrics seem to tell a similar story of an economy of avoidance and encounter implicating pedestrians and commercial areas.

2.5. Configurational categories: Parallel articulations of encounter and avoidance

Mapping some of the descriptive data illustrates how linearity and centrality do not always coincide with the same places at different radii and distance metrics. Places like Eaton Centre or Complexe Desjardins can be characterized as having a certain quality as an enclave, but Eaton Centre has a linearity that means it does not only stock, it also permits potential flows of pedestrians to deviate. It articulates a certain avoidance to the street while reinforcing an interior linearity that affords an encounter beneath certain street blocks. It is evident that several of the commercial locations around the Indoor City on the surface support an enclaving or stocking of commercial activities. Overall, however, these borders tend to fluctuate at different scales. It is therefore more difficult to define clear boundaries, for fear of a loss of interpretative capacity. Moreover, a conventional clustering technique (like k-means or two-step) would place each commercial location in a single cluster, based on a particular choice of variables and following a process of trial and error. To judge the output would require relying on pre-given ideal forms (abstract universals), and this would place us back in typo-morphological analyses, even if such a choice could be argued using evidence from previous studies. An additional problem is posed by the fact that centrality in an urban movement network tends to be maintained for several scales of movement before shifting to other, stronger attractors. This 'pervasive centrality' means that different metrics may tell similar stories, such as the pedestrian and commercial area accessibility at 400 m presented in the previous section.[45] Statistically, this poses the problem of multicollinearity, making it difficult to explore pervasive centrality in statistical models.

Rather than cluster analysis, the study used the dimension reduction method of principal component analysis (PCA). PCA identifies a series of categories (principal components) in the data to which each case is more or less a member (represented as principal component scores). It reduces the dimensionality of the data while "preserving as much 'variability' (i.e. statistical information) as possible" by first placing normalized variables in a correlation matrix and then extracting a series of linear functions (principal components) that are mutually uncorrelated.[46] A PCA was run on a standardized version of the 44 accessibility metrics in SPSS, including distance to the nearest metro station.[47] Of the 44 components produced by the PCA, eight described 87.5% of the variance in the dataset and had an eigenvalue over the cutoff value of 1.000 (Figure 2.12, Table 2.4).[48] Each commercial location is assigned a principal component score, which measures its degree of similarity to the component—or, rather, the extent to which the centrality metrics captured by each principal component (configurational category) characterizes the centrality of a food or retail location.

Descriptive names were given to each of the components using the variables for which the loading scores were the highest. The first principal component (PC), *400m commercial and pedestrian to-movement*, describes 14.7% of the variance and captures access to surface area and pedestrians at a 5-minute walking distance (400 m) and distance to metro, all which tell a similar configurational story (Figure 2.14). Centrality to pedestrians and outdoor commercial area load the highest (Table 2.5), which is not surprising given

[45] Hillier, "Spatial Sustainability in Cities: Organic Patterns and Sustainable Forms."

[46] Ian T. Jolliffe and Jorge Cadima, "Principal Component Analysis: A Review and Recent Developments," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 374, no. 2065 (April 13, 2016): 1.

[47] Sampling adequacy of 0.890 (Kaiser-Meyer-Olkin Measure of SA), $p<0.001$

[48] The more even distribution of variance among the components is due to the varimax rotation, which is commonly used to produce an orthogonal matrix and render the loading coefficients easier to interpret. However, this replaces the successive maximization of the components, see Jolliffe and Cadima, "Principal Component Analysis."

Figure 2.12. Principal Component Analysis revealed eight configurational categories that describe 87.5% of the information in the original data.

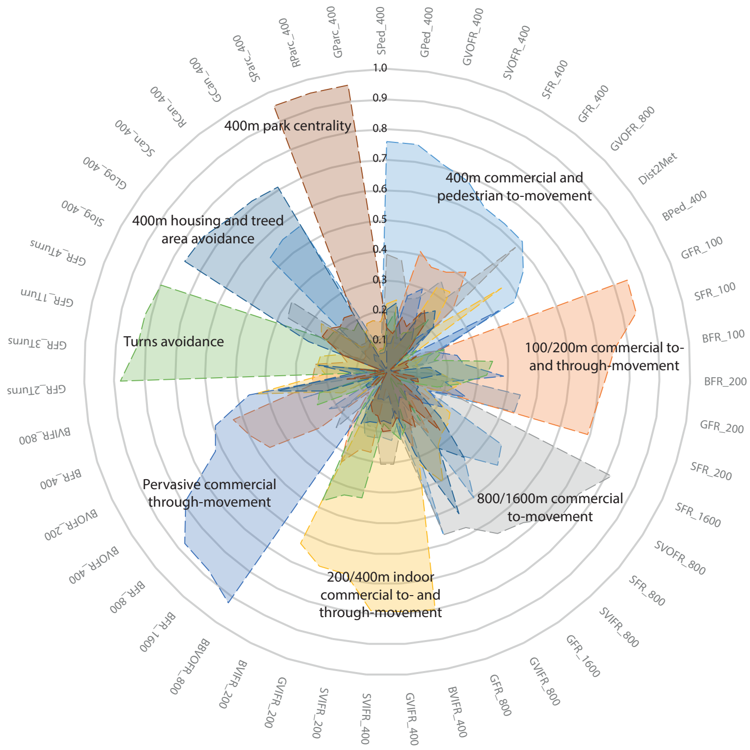


Table 2.4. Eight principal components describe 87.5% of the original variance of the collective variables.

Principal Component	% of the variance
1: 400m commercial and pedestrian t-movement	14.7
2: 100/200m commercial to- and through-movement	12.6
3: 800/1600m commercial to-movement	11.6
4: 200/400m indoor commercial to- and through-movement	11.3
5: Pervasive commercial through-movement	10.9
6: Turns avoidance	9.6
7: 400m housing and treed area avoidance	9.0
8: 400m park centrality	7.8

that being central to outdoor pedestrian counts likely parallels the same accessibility to outdoor commercial area. The distance to the metro station loads negatively, because the decrease in distance to the nearest metro station tends to follow an increase in outdoor pedestrian and commercial area centralities. Mapping the PC scores shows the degrees to which each location is similar or dissimilar to this story (Figure 2.13). The impact of the metro is evident in the higher values around metro stations, but the most similar locations border Ste-Catherine Ouest (after St-Laurent towards the west) and the commercial areas from Station McGill to Station Square Victoria. The values tending towards blue tell a contrasting story (the location is highly dissimilar to this principal component) and can reveal something about the logics of avoidance. In this case there is a strong tendency for the bluest areas to be nearer to the treed areas, suggesting that the logic of encounter among commercial

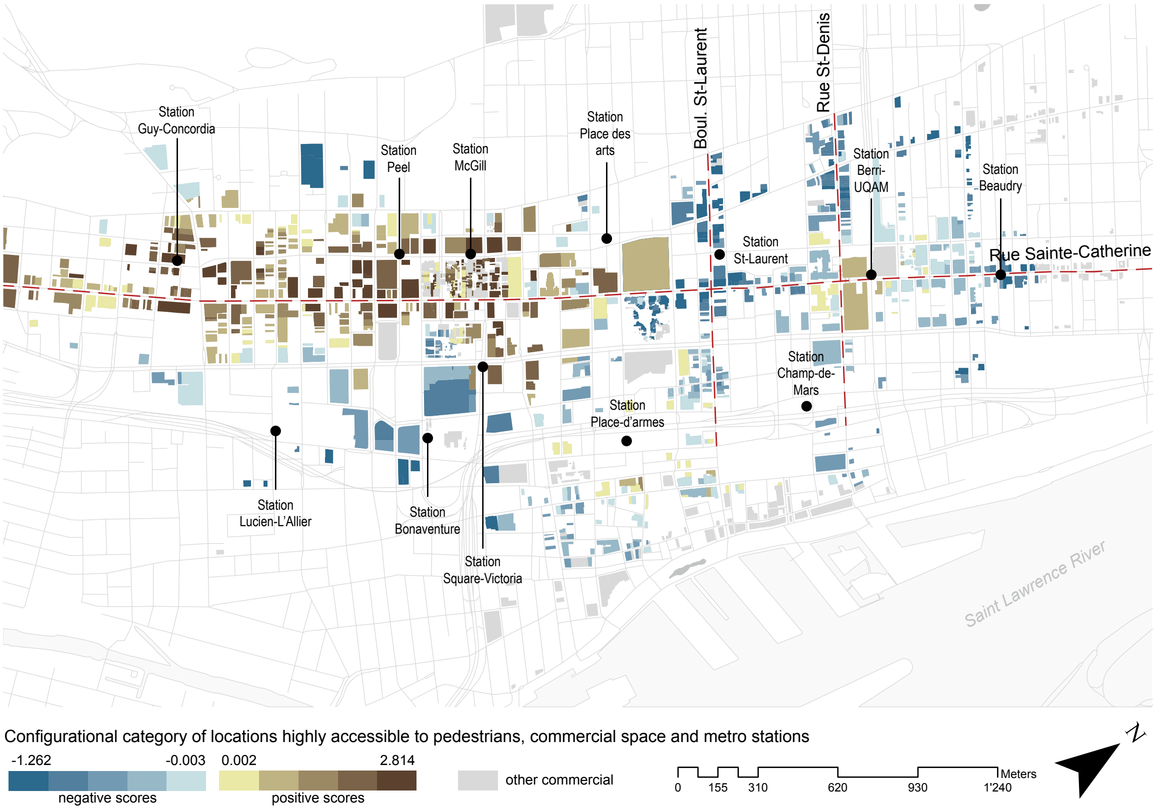


Figure 2.13. Configuration category of locations highly accessible to pedestrians, commercial space and metro stations at 400m.

Figure 2.14. Diagrammatic representation of the configurational characteristics captured by 400m commercial and pedestrian to-movement.

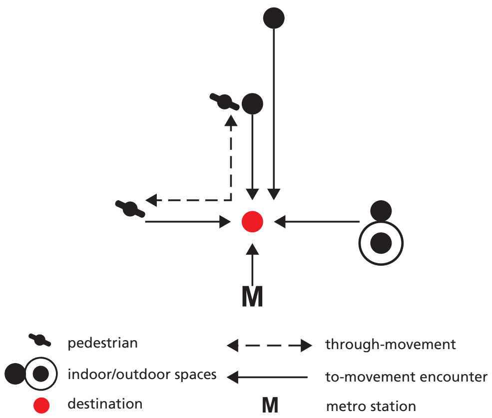


Table 2.5. Loading scores for variables captured by principal component 1, 400m commercial and pedestrian to-movement.

Variables of Component 1 (14.7% variance)	Loading Score
Outdoor pedestrian centrality @ 400m (straightness)	0.760
Outdoor pedestrian centrality @ 400m (gravity)	0.758
Outdoor pedestrian centrality @ 400m (betweenness)	0.480
Outdoor commercial area centrality @ 400m (gravity)	0.706
Outdoor commercial area centrality @ 400m (straightness)	0.684
Combined commercial area centrality @ 400m (straightness)	0.631
Combined commercial area centrality @ 400m (gravity)	0.623
Outdoor commercial area centrality @ 800m (gravity)	0.619
Distance to nearest metro station (in meters)	-0.558

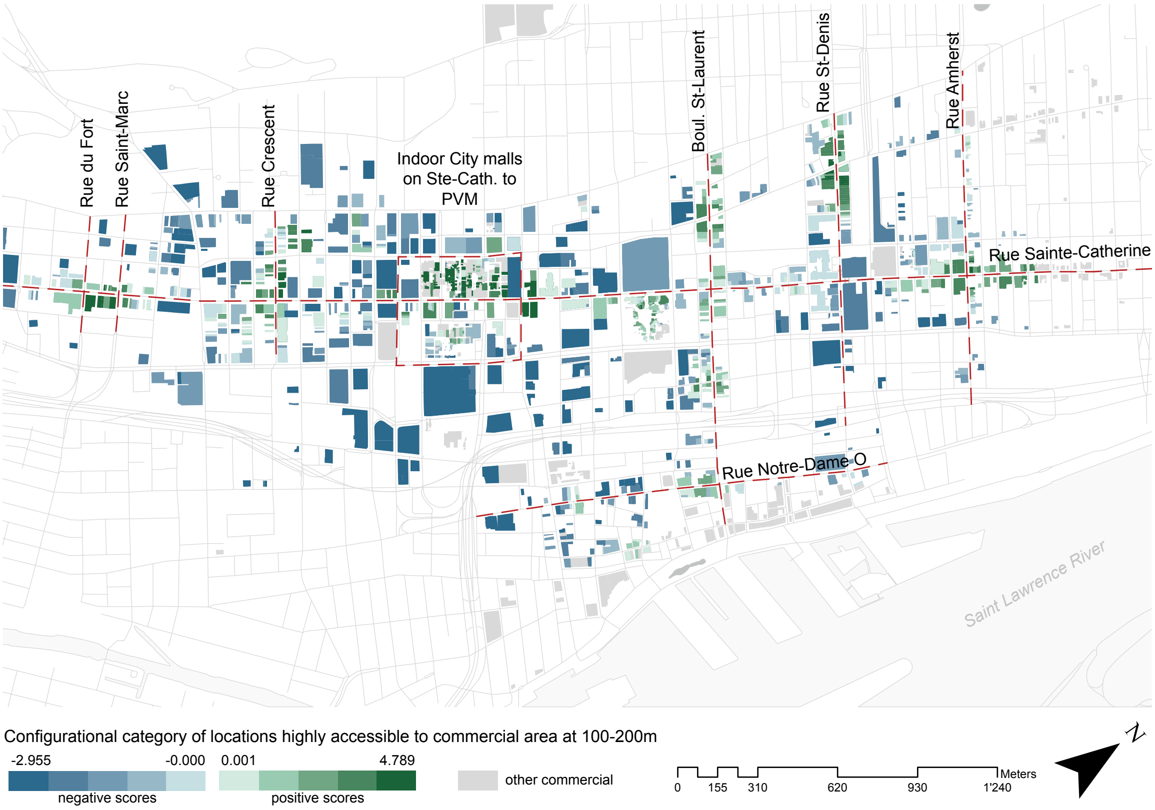


Figure 2.15. Configurational category of locations highly accessible to commercial area at 100-200m

Figure 2.16. Diagrammatic representation of the configurational characteristics captured by 100/200m commercial to- and through-movement.

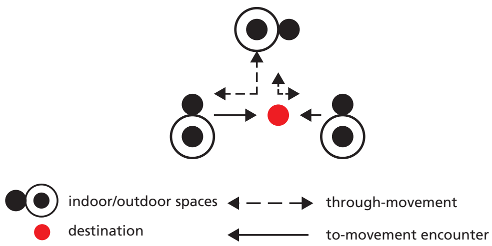


Table 2.6. Loading scores for variables captured by principal component 2, 100/200m commercial to- and through-movement.

Variables of Component 2 (12.6% variance)	Loading Score
Combined commercial area centrality @ 100m (gravity)	0.847
Combined commercial area centrality @ 100m (straightness)	0.846
Combined commercial area centrality @ 100m (betweenness)	0.754
Combined commercial area centrality @ 200m (gravity)	0.700
Combined commercial area centrality @ 200m (straightness)	0.694
Combined commercial area centrality @ 200m (betweenness)	0.722

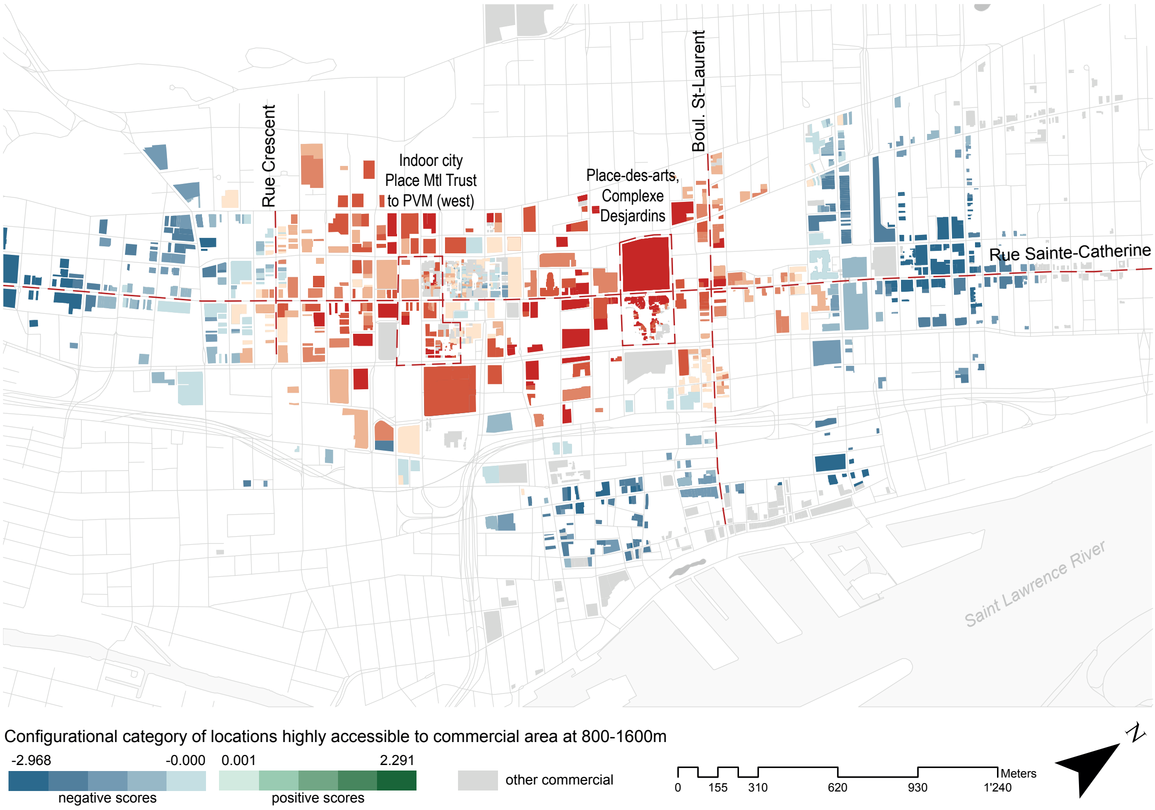


Figure 2.17. Configurational category of locations highly accessible to commercial area at 800-1600m

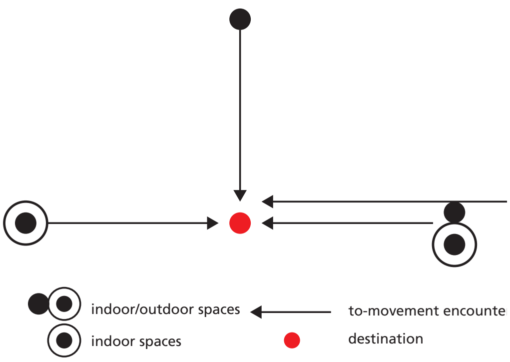


Figure 2.18. Diagrammatic representation of the configurational characteristics captured by 800/1600m commercial to-movement.

Variables of Component 3 (11.6% variance)	Loading Score
Combined commercial area centrality @ 1600m (straightness)	0.816
Combined commercial area centrality @ 1600m (gravity)	0.646
Combined commercial area centrality @ 800m (straightness)	0.745
Combined commercial area centrality @ 800m (gravity)	0.569
Outdoor commercial area centrality @ 800m (straightness)	0.748
Indoor commercial area centrality @ 800m (straightness)	0.668
Indoor commercial area centrality @ 800m (gravity)	0.574

Table 2.7. Loading scores for variables captured by principal component 3, 800/1600m commercial do-movement.

areas and pedestrians is accompanied by a smaller amount of treed areas within 400 meters.

The second principal component, *100/200m commercial to- and through-movement*, describes 12.6% of the variance and captures access to commercial area at 100 and 200 meters (Table 2.6). The gravity and straightness metrics to combined indoor and outdoor commercial area load the highest at 100 m, followed by the betweenness metric at 100 m and the same metrics at 200 m (Figure 2.16). This component may capture the spatial configuration underlying the tendency for movements around the Indoor city to be highly local, as observed by the study by Zacharias.[49] Mapping this category picks out the local concentrations of commercial locations, whether indoors or outdoors (Figure 2.15). Clusters are observable all over town, often at intersections or around the Indoor City, suggesting that this latter is part of a series of local networks of commercial spaces. There does not appear to be a major difference between the indoors and outdoors here.

The third PC, *800/1600m commercial to-movement*, constitutes the logics of encounter that occur at the scale of 10 to 20-minute walks (800-1600 m). Being central to both indoor and outdoor spaces at 1600 m distances load highest in this component and capture a pervasive centrality that includes gravity and straightness centrality at 800 meters to both indoor and outdoor commercial area (Table 2.7). This category reveals the degree to which locations are likely to be destinations at larger movement distances along the pedestrian network (Figure 2.18). The food and retail locations in Complexe Desjardins seem to be just as accessible as many outdoor locations along Ste-Catherine between Rue St-Laurent and Rue Crescent (Figure 2.17). The only other part of the Indoor City that belongs so well to this category is along the western edge of Place Montréal Trust and Place Ville-Marie, which are more directly connected to the street than some of the other commercial locations within Eaton Centre or Complexe Les Ailes. These latter tend to internalize and limit paths of entry and exit at all floors.

The fourth PC, *200/400m indoor commercial to- and through-movement*, resembles the second component, but rather than capture local centers formed by connectivity to all food and retail locations in the downtown, it considers *only* those that are indoors (2.19). Gravity, straightness and betweenness metrics at the 400 m network-radius load highest, followed by the same metrics at a 200 m radius (Table 2.8). Mapping the component scores reveals a higher degree of membership to the category among stores around the Indoor City (Figure 2.18). Oddly, the malls along Ste-Catherine, apart from Eaton Centre do not enjoy as high a local accessibility among each other—as if the neighboring outdoor commercial spaces were situated at a critical distance between the clusters of indoor spaces and

[49] Zacharias, "Underground Pedestrian Trips—trip Generation, Spatial Distribution and Activities in the Montréal Underground."

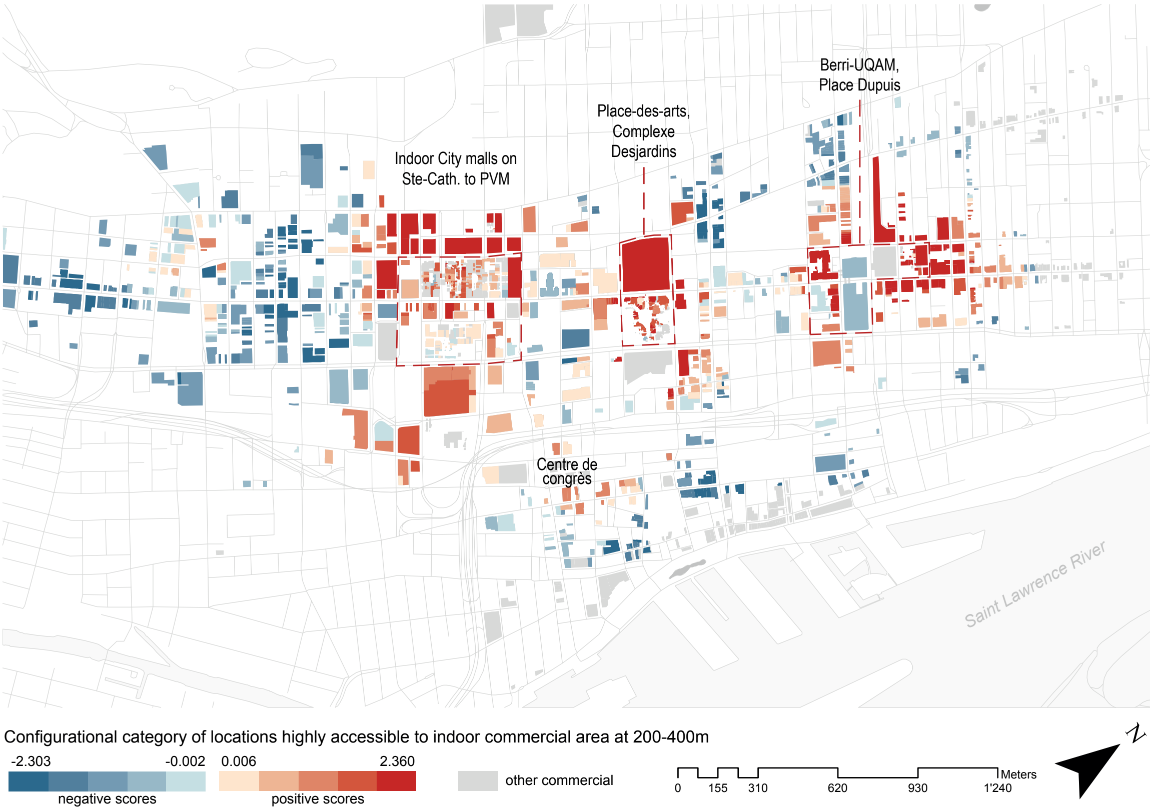


Figure 2.18. Configurational category of locations highly accessible to indoor commercial area at 200-400m

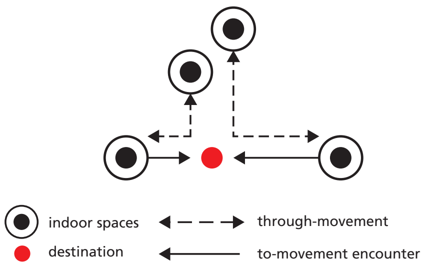


Figure 2.19. Diagrammatic representation of the configurational characteristics captured by 200/400m indoor commercial to- and through-movement.

Variables of Component 4 (11.3% variance)	Loading Score
Indoor commercial area centrality @ 400m (gravity)	0.794
Indoor commercial area centrality @ 400m (straightness)	0.788
Indoor commercial area centrality @ 400m (betweenness)	0.801
Indoor commercial area centrality @ 200m (gravity)	0.678
Indoor commercial area centrality @ 200m (straightness)	0.680
Indoor commercial area centrality @ 200m (betweenness)	0.632

Table 2.8. Loading scores for variables captured by principal component 4, 200/400m indoor commercial to- and through-movement.

adjacent outdoor ones (whose overall surface area is much higher). This is probably best explained by the presence of the betweenness metrics in this configurational category, which means that the higher values among outdoor locations are also capturing the fact that many origin-destination paths going to or from the Indoor City at 200 and 400 meters would pass in front of outdoor commercial locations. This is also why Eaton Centre is characterized better by this configurational category than its neighbors (Complexe les Ailes and Place Montréal Trust)—it is situated at the intersection of all origin-destination pairs to and from Place Ville Marie, the Central Station and Place Bonaventure to the south and the neighboring Indoor City locations along Ste-Catherine. Eaton Centre articulates an axial logic of encounter, locally within the Indoor City.

Principal components five and six are configurational categories that describe the metric and topological linearity of the spatial relationships between commercial locations. For the fifth PC, *Pervasive commercial through-movement,* betweenness measures tend to tell the same story at walking distances from 200 to 1600-meter network radii, as indicated by the loading scores (Table 2.9, Figure 2.21). When mapping the component scores, east-west armatures appear along Boulevard de Maisonneuve, Rue Ste-Catherine and Rue Notre-Dame Ouest and north-south axes appear in particular along Rue St-Denis, Boulevard St-Laurent, Rue McGill and Rue Crescent (Figure 2.20). The Indoor City is mostly removed from this logic of connectivity, except for Eaton Centre, which again sits at the intersection of two major corridors of the Indoor City.

PC six, *turns avoidance*, captures the commonalities between the turns measures. In producing this principal component, the dimension reduction actually gives us a logics of avoidance, which means that the metrics indicate less 'centrality' than 'peripherality', as indicated by the negative loading scores in the PCA (Table 2.10, Figure 2.23). The more negative the values, the greater the increase in accessible commercial space with each additional turn from the entry point (Figure 2.22). What is interesting is how the indoor locations are all least characterized by this configurational category, meaning their circuitous interiors (whether floor changes are effectuated by escalator or elevator) do not afford much increase in accessible commercial space. This may be similar to the logics of avoidance articulated with visible area, where the commercial strategy is to limit the viewable plane and to concentrate movements along labyrinthine, store-front rich armatures.

Principal component seven, *400m housing and treed area avoidance*, reveals that access to housing units and treed areas at 400 meters tends to follow a similar spatial distribution. Like component six, the variables load negatively, indicating a pervasive 'peripherality' of commercial locations to housing units and tree canopy area (Table 2.11, Figure 2.25). Mapping the component scores reveals that Place Dupuis and Complexe Desjardins are both

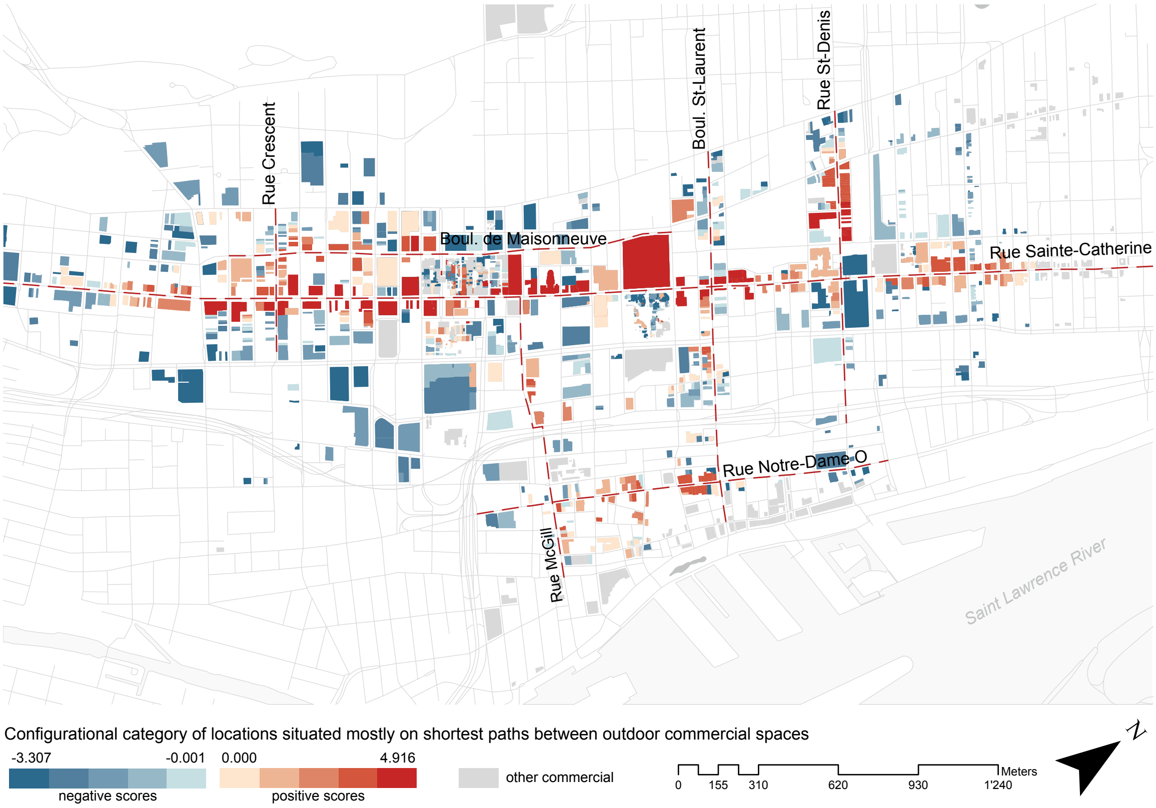


Figure 2.20. Configuration category of locations situated mostly on shortest paths between outdoor commercial spaces.

Figure 2.21. Diagrammatic representation of the configurational characteristics captured by pervasive commercial through-movement.

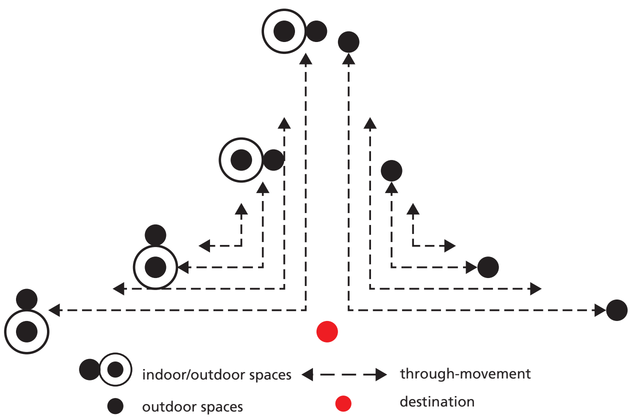


Table 2.9. Loading scores for variables captured by principal component 5, pervasive commercial through-movement.

Variables of Component 5 (10.9% variance)	Loading Score
Combined commercial area centrality @ 1600m (betweenness)	0.880
Combined commercial area centrality @ 800m (betweenness)	0.876
Combined commercial area centrality @ 400m (betweenness)	0.594
Outdoor commercial area centrality @ 800m (betweenness)	0.923
Outdoor commercial area centrality @ 400m (betweenness)	0.790
Outdoor commercial area centrality @ 200m (betweenness)	0.625
Indoor commercial area centrality @ 800 (betweenness)	0.461

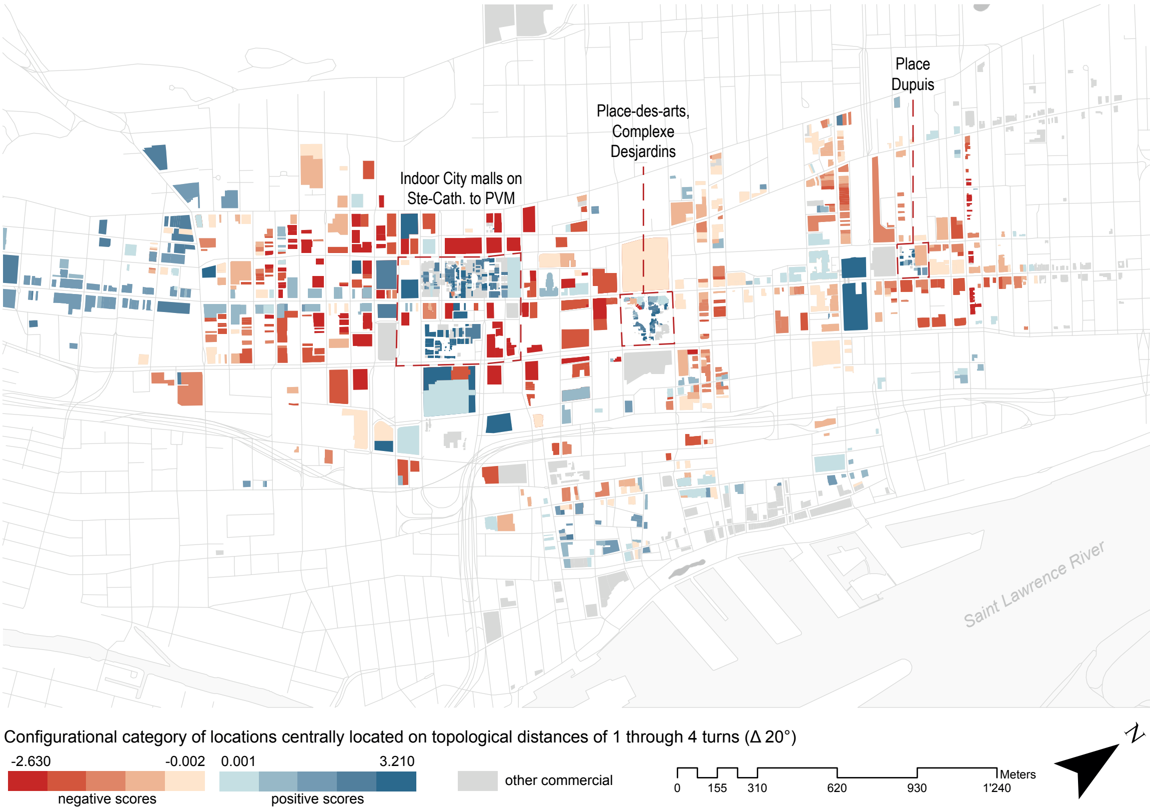


Figure 2.22. Configurational category of locations centrally located on topological distances 1 through 4 turns (angular changes greater than 20°)

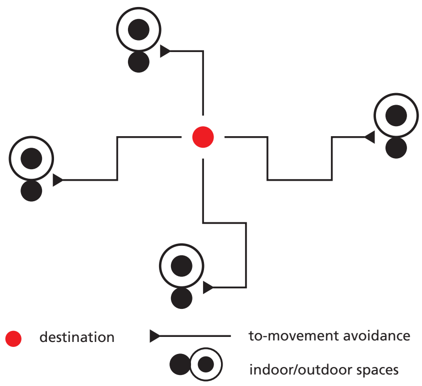


Figure 2.23. Diagrammatic representation of the configurational characteristics captured by turns avoidance

Variables of Component 6 (9.6% variance)	Loading Score
Combined commercial area 'peripherality' @ 1 Turn	-0.821
Combined commercial area 'peripherality'@ 2 Turns	-0.881
Combined commercial area 'peripherality'@ 3 Turns	-0.830
Combined commercial area 'peripherality'@ 4 Turns	-0.798

Table 2.10. Loading scores for variables captured by principal component 6, turns avoidance.

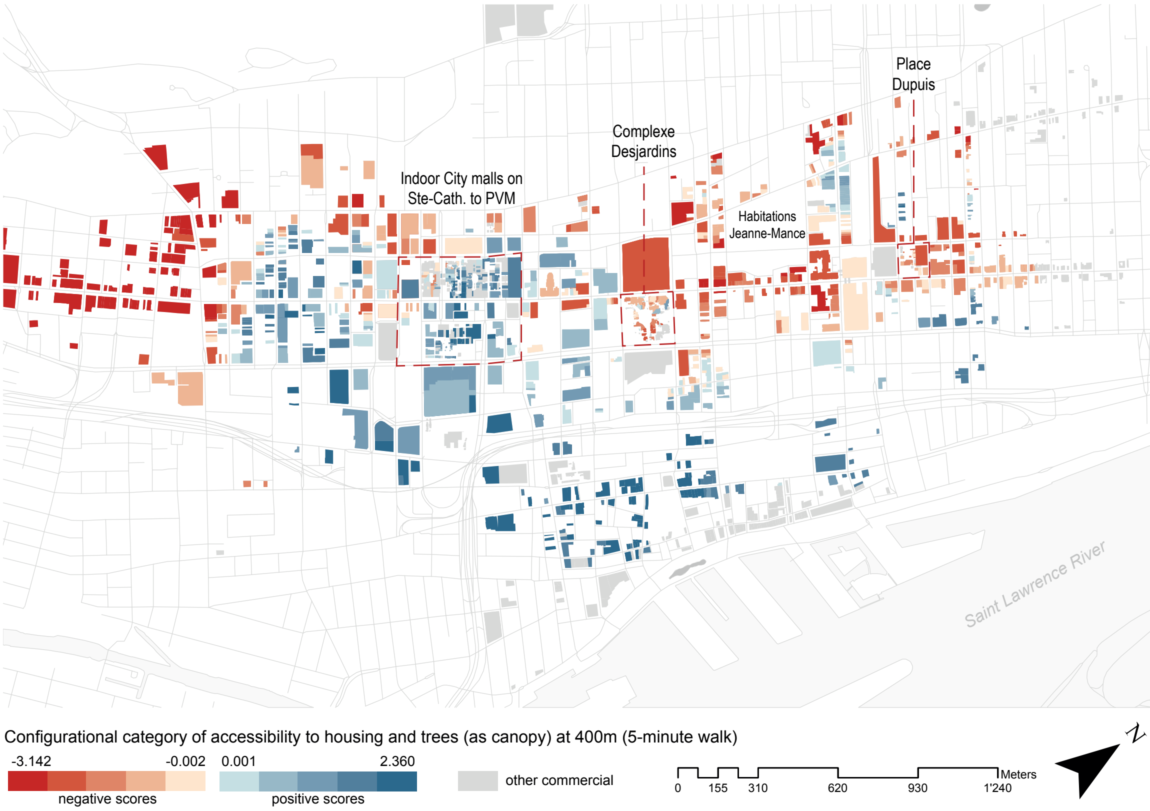


Figure 2.24. Configurational category of accessibility to housing and trees (as canopy) at 400 meters.

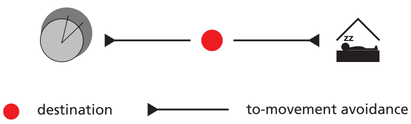


Figure 2.25. Diagrammatic representation of the configurational characteristics captured by 400m housing and treed area avoidance.

Table 2.11. Loading scores for variables captured by principal component 7, 400m housing and treed area avoidance.

Variables of Component 7 (9.0% variance)	Loading Score
Housing unit 'peripherality' @ 400m (straightness)	-0.761
Housing unit 'peripherality' @ 400m (gravity)	-0.752
Tree canopy 'peripherality' @ 400m (straightness)	-0.725
Tree canopy 'peripherality' @ 400m (reach)	-0.719
Tree canopy 'peripherality' @ 400m (gravity)	-0.708

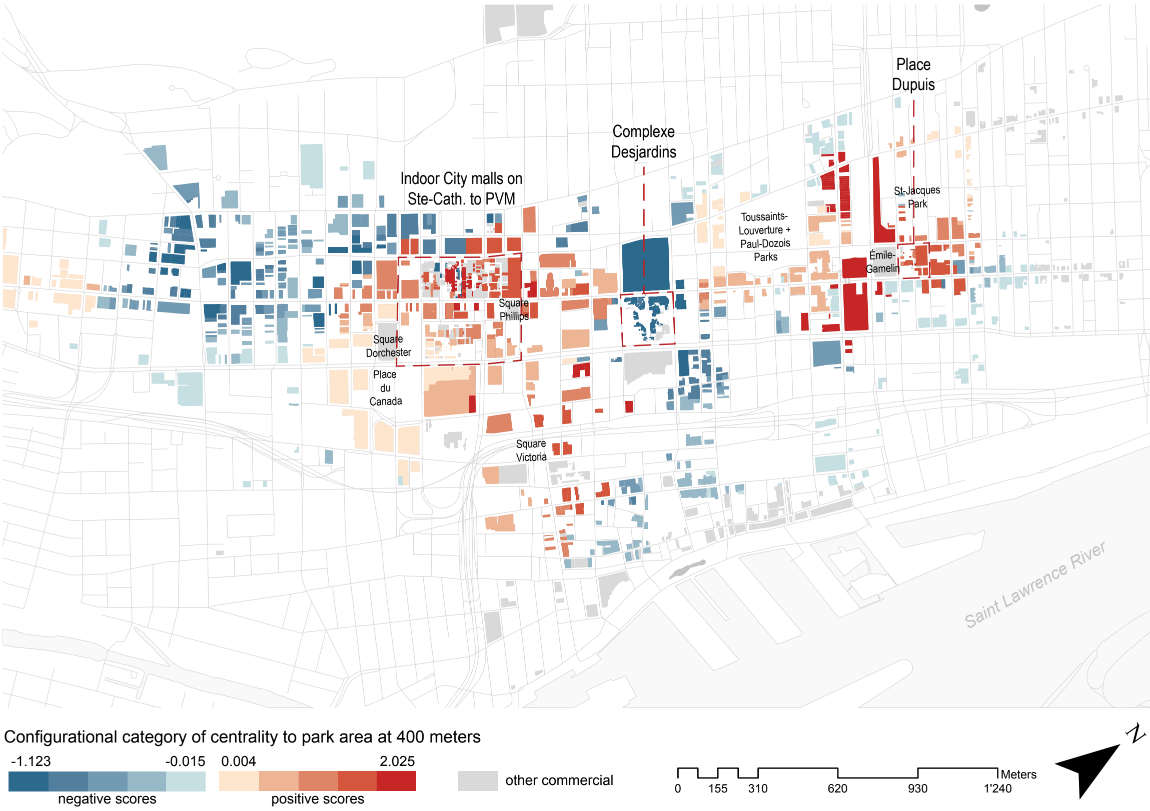


Figure 2.26. Configuration category of centrality to park area at 400m.

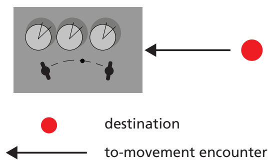


Figure 2.27. Diagrammatic representation of the configurational characteristics captured by 400 m park centrality

Table 2.12. Loading scores for variables captured by principal component 8, 400 park centrality.

Variables of Component 8 (7.8% variance)	Loading Score
Park centrality @ 400m (gravity)	0.953
Park centrality @ 400m (reach)	0.954
Park centrality @ 400m (straightness)	0.954

located near parks, open areas and surrounded by either residential neighborhoods or large housing projects (like Habitations Jeanne-Mance with over 500 units in 2004) (Figure 2.24). The Indoor City malls along Ste-Catherine and around Place Ville-Marie are more removed from residential areas and the floor-area-ratio of buildings here tends to leave less space for open areas with trees. Although one would think that housing and treed areas might follow a similar spatial configuration as parks, this is not the case in this portion of Montreal.

The eighth principal component, *400m park centrality*, alone captures the gravity, straightness and reach metrics of accessibility to parks and public squares (Table 2.12, Figure 2.27). In 2004, before the development of the Place-des-Arts cultural hub, Complexe Desjardins was not near designated park space or public places, despite being near housing and treed areas (Figure 2.26). The malls along Ste-Catherine are near neither housing nor treed areas, but they are close to several parks including Square Dorchester and Square Philips. These are more urban parks with fountains and benches than vegetation.

2.6. The heterotopiality of the Indoor City

Each food and retail location is either similar or dissimilar to the eight configurational categories as captured by the principal component score. Separating indoor and outdoor spaces and graphing the minimum, mean and maximum values (Figure 2.28) suggests that there may be some important configurational differences. First, indoor locations tend to be less equally connected to indoor and outdoor commercial area at short distances (100 and 200 m) than outdoor spaces. Outdoor establishments in the study area around the Indoor City enjoy proximity to both indoor and other outdoor establishments, whereas indoor locations, perhaps because of the distance required are locally less connected to the outdoors. Second, outdoor establishments tend to be characterized by a greater accessibility to outdoor commercial area at 800 and 1600 m network distances. This is hardly surprising. Third, the spatial configuration of indoor food and retail locations follows more a logic of turns avoidance than outdoor spaces do, which, as mentioned previously, is likely due to the circuitous path layout characteristic of multi-level mall design. Finally, Figure 2.13 also suggests that outdoor spaces are, to a smaller degree than indoor spaces, configured to be peripheral to housing and treed areas, which is likely the effect of being in the CBD, where there is less housing and fewer tree-covered areas.

The categories of indoor and outdoor may, however, be an inadequate classification. If the indoor-outdoor boundary is the first configurational starting point, it is still uncertain whether this dualism has the greatest explanatory power. It is also the objective here to stick to configurational descriptions of the urban spatial

Figure 2.28. Comparing indoor and outdoor spaces reveals some important configurational differences between them

network and avoid political ('public' or 'private') or social (target clientele) forms for describing encounter and avoidance. Boundaries in the logics of encounter and avoidance are identified by mapping hotspots in the principal component scores. The hotspot analysis calculates the statistically highest and statistically lowest values with non-significant values in between (Figure 2.29).[50] For the first principal component *(400m commercial and pedestrian to-movement),* the statistically highest values suggest that the largest encounter is around the Place Montréal Trust to Place de la Cathédrale sector of the Indoor City along Ste-Catherine. Place Ville-Marie and Complexe Desjardins are both in a logic of avoidance, while Place Dupuis near Berri-UQAM is neutral or indifferent in its spatial configuration. This suggests that the four commercial centers participate in a local convexity (enclaving or attracting) of commercial area and pedestrians along with the metro stations. There is a sort of stocking of intensities in this logic. In contrast, Place Ville-Marie and Complexe Desjardins appear to slightly remove themselves from this. While their avoidance cannot be interpreted as an 'expulsion' of intensity (or urbanity), they are 'attracting' or stocking something else.

In order to simplify, the interpretation of heterotopiality looks at three locations in particular: Place Ville-Marie (built 1950s), Eaton Centre, and Complexe Desjardins (both built in the 1970s with

[50] Conducted in ArcGIS using the Getis-Ord Gi* statistic.

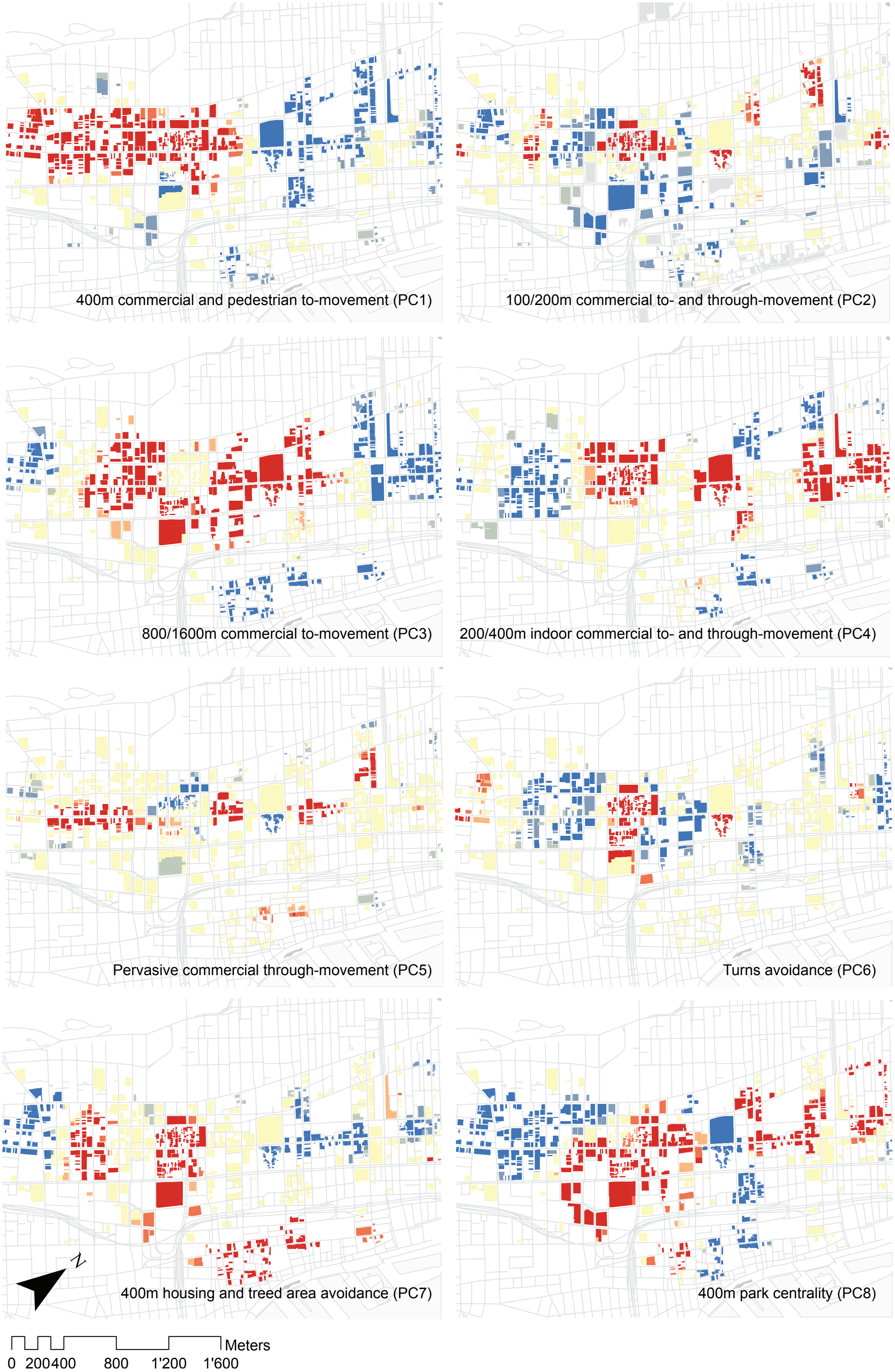


Figure 2.29. Hotspot analyses identifying the areas of statistically high (red) and low (blue) degrees of membership to the principal component.

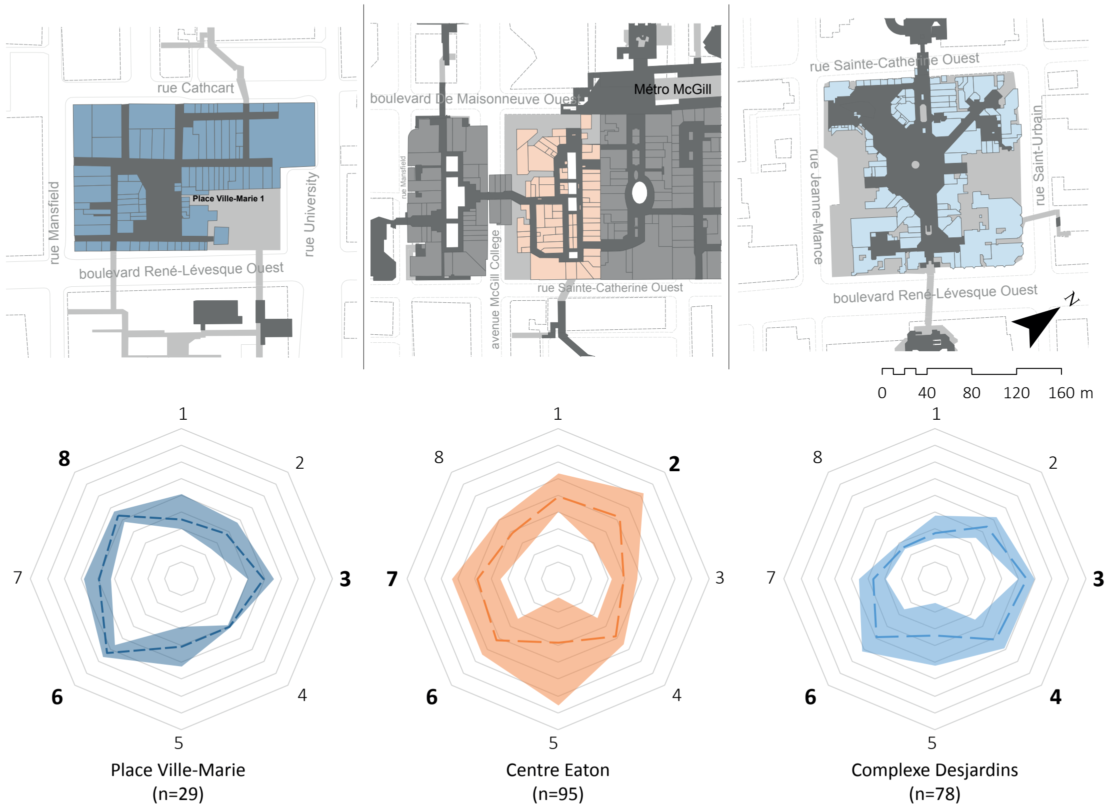


Figure 2.30. Place Ville-Marie, Eaton Centre and Complexe Desjardins are different in their interior configuration as well as in their configurational relationship to the surrounding urban fabric.

major renovations completed on the former in the early 1990s).[51] Place Ville-Marie is comprised of an underground grid-like series of corridors with a central concave space where tables and chairs are laid out and several cafés provide food and drinks (Figure 2.30). Place Ville-Marie's location orchestrates encounter with other food and retail spaces at distances of 800 to 1600 meters along shortest and straightest paths and to a lesser degree to indoor food and retail spaces at 200 and 400 meters where it is near the tunnel leading to Eaton Centre. Its logic of avoidance is most apparent in its distancing itself at 400 meters from concentrations of pedestrians, metro stations and indoor and outdoor commercial spaces at this particular distance. This, however, is mostly for the portion of the commercial spaces that border the corridor leading to the main station, with the ones closer to the Eaton axis being indifferent to this configurational category. Like Eaton Centre and Complexe Desjardins, its avoidance is articulated in the turns metric. It differs in its lack of avoidance in the linearity of betweenness. Perhaps due to its connectivity with the outdoors (its permeability), the food and retail locations in Place Ville-Marie sit along shortest routes between origins and destinations at 800 to 1600 meters (or 10- to 20-minute walks (Figure 2.31)).

Complexe Desjardins is characterized by a radial layout surrounding a central open area with a fountain and three floors of shopping, one below and one above ground (Figure 2.32). It is

[51] Michel A Boisvert, *Montréal et Toronto : villes intérieures* (Montréal: Presses de l'Université de Montréal, 2011).

Figure 2.31. View of interior atrium food court space of Place Ville-Marie. (source: http://provencherroy.ca/images/upld/edifice-a-bureaux-5-place-ville-marie_112933.jpg)

Figure 2.32. Central atrium space of Complexe Desjardins. (source: https://d7100shooter.files.wordpress.com/2013/07/dsc_1956_3000x2000.jpg)

linked to the north by a tunnel and a (sometimes pedestrian-only in the summer) segment of Rue Ste-Catherine and to the south to Complexe Guy-Favreau (an administrative government building) via a tunnel under Boulevard René-Lévesque. Like Place Ville-Marie, its location does not place it in a logic of encounter with food and retail area, metro stations or even outdoor concentrations of pedestrians at a distance of 400 meters. Its avoidance is also revealed by the betweenness configurational category—for food and retail spaces, it is never on-the-way. The spatial configuration of Complexe Desjardins orchestrates a logic of encounter which goes from the highly local (100-200m) to the medium (200-400m) and global (800-1600m) distances. Its configuration accumulates a sort of stock of commercial spaces, as a multiscale enclave, but its linearity is one of avoidance and removal. In four turns from several storefronts, a pedestrian might not be anywhere near an exit.

Eaton Centre's spatial configuration, with its two floors above and two below ground, differs from the other indoor commercial centers by being well connected to both the indoors and outdoors

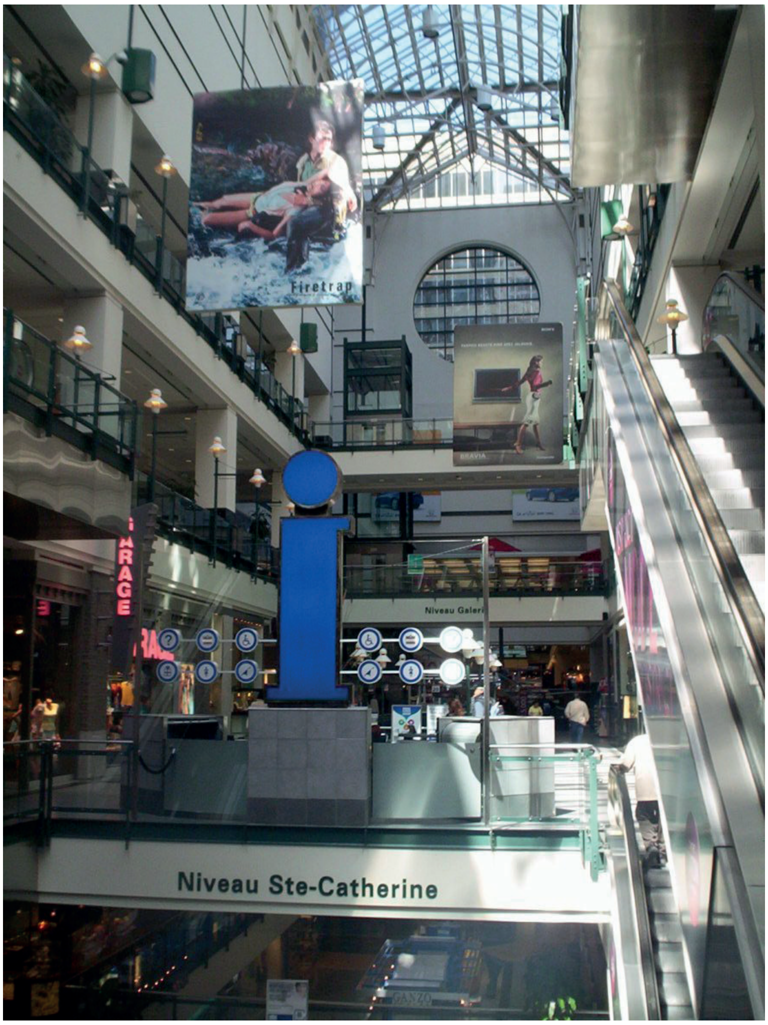


Figure 2.33. Multi-level atrium space of Eaton Centre, view from street level. (source: http://images.boomsbeat.com/data/images/full/37451/4-jpg.jpg)

(Figure 2.33). It contributes as much to directing and sorting as it does to stocking or capturing potential passersby. Unlike Place Ville-Marie or Complexe Desjardins, it is situated in (and perhaps constitutes) part of the heart of the spatial network of commercial spaces, pedestrians and metro stations. It is locally well-connected and articulates a spatial logic of encounter with both indoor and outdoor commercial spaces in its immediate (100-200) proximity. Although its configuration is indifferent at 800 and 1600-meter network radii to connectivity to commercial spaces, it is surrounded by food and retail locations that appear to draw from it as an enclave-like concentration of commercial space. Its heterotopiality appears, like Place Ville-Marie and Complexe Desjardins, to be related to its participation in the linearity of the spatial network of commercial spaces on the topological (turns) and metric (betweenness) distances.

The configurational differences between Place Ville-Marie, Complexe Desjardins and Eaton Centre demonstrate the inability to develop an unambiguous account of the heterotopiality of indoor and underground spaces. Indeed, this heterotopiality appears to be most evident in their axial articulation of avoidance, meaning they have the potential to attract food and retail movement, but they would be likely to limit many of these movements. Certainly, Eaton Centre and Desjardins can be characterized in this way, but Place Ville-Marie cannot. The enclaves of commercial spaces they form do, however, seem to afford a logic of encounter between indoor and outdoor parts of the city. The question is then how these different configurational characteristics endow food and retail locations with a particular value. Does this economy of communication, of avoidance and encounter, come with a price and how is this price distributed spatially? To explore possible answers to this question, the next section will build a spatial econometric model of the configurational categories, using several other characteristics of Montreal food and retail locations and rent cost from 2004.

2.7. Deciphering rent per square meter: What is the 'value' of spatial configuration for the urban indoor and outdoor pedestrian network?

2.7.1. 'Global' models: Spatial econometrics

The observed configurational differences within the Montreal downtown may or may not contribute to the economic value of each food and retail location. The objective is not to judge whether one configuration is better than another, but rather to see which appear to endow indoor and underground places with value and to see how the level of impact varies geographically. As mentioned at the beginning of the chapter, it is in exploring this interaction that more careful experimental production and control is necessary. For this reason, the regression model constructed here adopts methods from spatial econometrics, and is carried out using the open source software GeoDaSpace on the 1541 indoor and outdoor food and retail locations.[52] A log-transformed version of rent in Canadian dollars per square meter constitutes the dependent variable.[53] Mapping untransformed rental values reveals that they are highest around the Place Montréal Trust to Place de la Cathédrale commercial centers down to Place Ville-Marie and the Central Station (Figure 2.34). They are lowest around Boulevard St-Laurent, Rue St-Denis and Rue Amherst north of Ste-Catherine and along Ste-Catherine between these three streets.

The independent variables include the eight principal components, the surface area of each location, the number of floors it is below street level (to test the advantage of being underground), the amount of ground area visible in front of the store, the density of commercial activities on the parcel, whether or not the location is indoors and outdoors and whether the location is situated on an easily crossable street (Tables 2.2, above, and 2.13). The objective is to identify the independent variables that contribute most to

[52] https://geodacenter.asu.edu/geodaspace-mode

[53] Rental value is log-transformed to account for skewness and ensure that its distribution is a normal as possible.

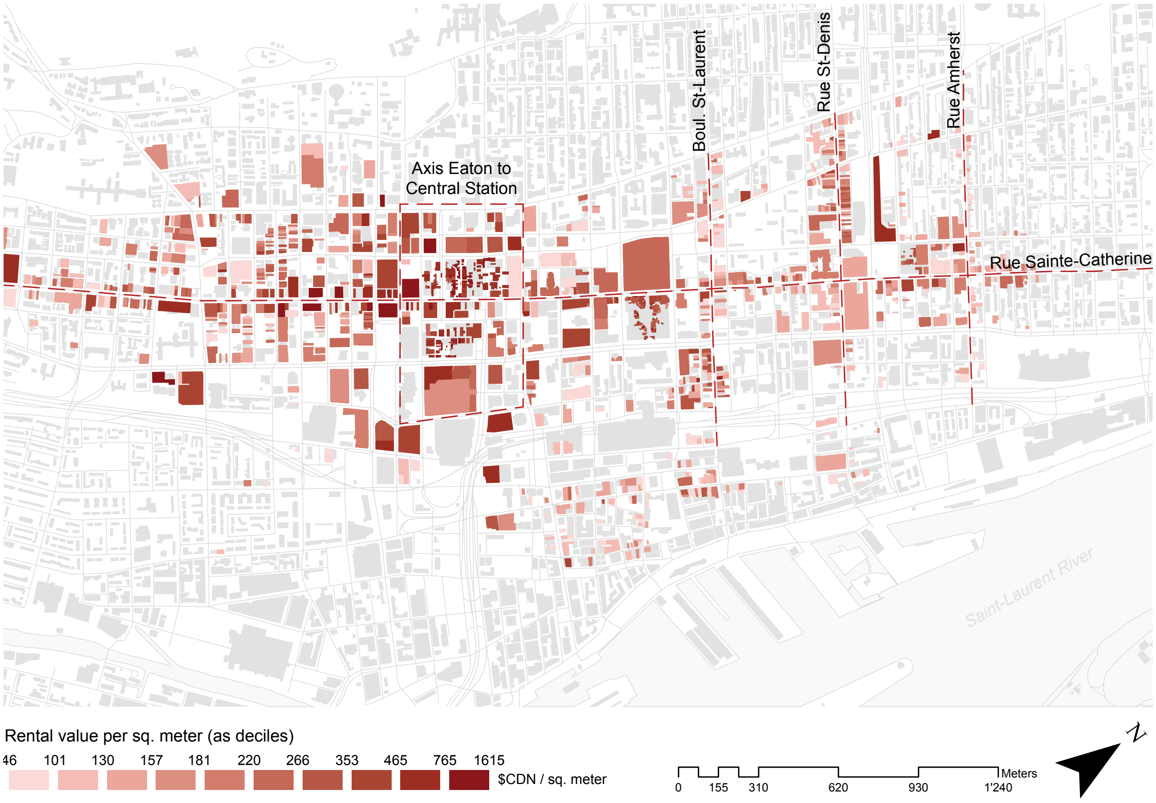


Figure 2.34. Distribution of rental values of food and retail locations.

Table 2.13. Additional variables included in the spatial econometric models

	Mean Outdoor (Indoor)	Min. Outdoor (Indoor)	Max. Outdoor (Indoor)
Corridor/street is crossable (frequencies)	Yes: n=322 (n=332) No: n=887 (n=0)	N/A	N/A
Density of food and retail activities on parcel	0.32 (0.56)	0	1
Floors below ground level (frequencies)	0 (0.70)	0 (0)	0 (1)

explaining the spatial variance in rent per square meter. An initial evaluation of potentially strong correlations was conducted as bivariate tests between the dependent and independent variables, for the whole dataset and then separately for indoor and outdoor locations (Table 2.14). The Spearman tests reveal the importance of being indoors or outdoors and of store surface area, which shows that smaller locations rent for more per square meter (the negative sign). Among the configurational categories, the first, third, fourth and sixth are most significant individually for the whole sample. The first and seventh are the most significant for indoor locations and the first, third and fifth principal components have the highest rho values when correlated with the rental values of outdoor food and retail spaces only. These individual correlations do not, however,

Dependent variables	Combined		Indoor		Outdoor	
Descriptive properties						
Surface Area (m2)	-0.344	***	-0.527	***	-0.228	***
Floors below ground level	0.495	***	0.162	**		
Area visible from entry (m2)	-0.400	***	0.029		0.022	
Density of food and retail activities on parcel	0.237	***	0.341	***	0.052	
Location is indoors rather than outdoors (bivariate)	0.605	***				
Entry is on a street/corridor crossable anywhere (bivariate)	-0.185	***			-0.017	
Configurational categories (principal components)						
400m commercial and pedestrian t-movement (PC 1)	0.325	***	0.402	***	0.353	***
100/200m commercial to- and through-mvmnt (PC 2)	0.233	***	0.171	**	0.075	**
800/1600m commercial to-movement (PC 3)	0.306	***	-0.239	***	0.285	***
200/400m indoor to- and through-mvmt (PC 4)	0.294	***	-0.067		0.078	**
Pervasive commercial through-movement (PC 5)	0.116	***	0.101		0.313	***
Turns avoidance (PC 6)	0.338	***	-0.012		-0.077	**
400m housing and treed area avoidance (PC 7)	0.113	***	0.377	***	-0.073	*
400m park centrality (PC 8)	-0.078	**	0.109	*	-0.131	***

Significance level of spearman's rho: *** ρ<0.001, ** ρ<0.01, * ρ<0.05

Table 2.14. Bivariate correlations for independent variables with the dependent variable (Value per m^2 in $CDN)

take into account the combinations of these variables in a single model.

An initial Ordinary Least Squares (OLS) regression using a 400 m spatial weights matrix[54] (which situates the points in a topological space and is used to solve the regression equation with matrix algebra) was conducted in order to evaluate initial performance of the model and look at the diagnostics for multicollinearity, heteroscedasticity and spatial dependence. The selection of independent variables (which dropped 'floors below ground level', 'density of activities' and the eighth principal component during model specification) describes around 62% of the variation in rental prices. Multicollinearity is very low at 14.81 (where 30 is the threshold[55]), which may be due to the fact that the principal components are orthogonally rotated (and therefore not correlated). The heteroscedasticity diagnostics showed that the variance of the dependent and independent variables is not evenly distributed, requiring a control parameter, the Kelejian and Prucha heteroscedasticity estimator.[56] The OLS regression indicated (in the Robust LM error) that the model had spatially autocorrelated omitted variables (what is 'unknown' is correlated in space); and found (in the Robust LM lag) strategic spatial interaction between the cases, meaning the values of one location are influenced by the values of its neighbors (Table 2.15). To control for this, it was necessary to use a combined spatial error and spatial lag regression model,[57] which adds to the equation an error and a lag parameter

54 The weights matrix was calculated in ArcGIS as an adjacency matrix and then converted for use in GeoDaSpace. The radius was established by looking for the distance at which all food and retail locations had at least one neighbor.

55 Luc Anselin and Sergio J. Rey, *Modern Spatial Econometrics in Practice: A Guide to GeoDa, GeoDaSpace and PySAL* (Chicago, IL: GeoDa Press, 2014).

56 Ibid.

57 Ibid.

Table 2.15. Ordered Least Squares Model for indoor and outdoor commercial spaces (n=1541). Spatial dependence diagnostics based on a 400-meter distance band network spatial weights matrix.

Variable	coefficient	signif.	t-statistic
Constant	2.5830	***	79.1525
Descriptive properties			
Surface Area (m^2)	-0.1395	***	-12.5129
Floors below ground level			
Area visible from entry (m^2)	0.0005	***	3.4577
Density of food and retail activities on parcel			
Location is indoors (bivariate)	0.3746	***	10.1160
Entry is on a street/corridor crossable anywhere (bivariate)	-0.0418	**	-2.8477
Configurational categories (Principal Components)			
400m commercial and pedestrian t-movement (PC 1)	0.1100	***	19.6881
100/200m com. to- and through-mvmnt (PC 2)	0.0361	***	5.5167
800/1600m commercial to-movement (PC 3)	0.0650	***	10.9738
200/400m indoor to- and through-mvmt (PC 4)	0.0379	***	5.2527
Pervasive commercial through-movement (PC 5)	0.0537	***	9.0724
Turns avoidance (PC 6)	0.0440	***	4.0647
400m housing and treed area avoidance (PC 7)	0.0213		3.5185
400m park centrality (PC 8)			
Fit Statistics			
R2 (adjusted)	0.6226		
F-Statistic	231.97		
Log likelihood	290.53		
Multicollinearity condition number	14.81		
Test on normality of errors (Jarque-Bera)	178.07	***	
Diagnostics for Heteroscedasticity			
Breusch-Pagan Test	235.27	***	
Koenker-Bassett Test	129.80	***	
Diagnostics for Spatial Dependence			
LM (lag)	351.33	***	
Robust LM (lag)	7.98	**	
LM (error)	398.54	***	
Robust LM (error)	55.199	***	
LM (SARMA)	406.52	***	

Significance level of spearman's rho: *** ρ<0.001, ** ρ<0.01, * ρ<0.05

(Figure 2.35). Essentially, the diagnostics conducted here render the results of the OLS dubious and likely biased.

As opposed to the OLS regression (which is relatively common in configurational studies), the combined spatial error and lag model (the combo model) accounts for both spatial autocorrelation in the dependent variable (the rent of one place depends on its neighbors) and in the error term (potentially missing variables are clustered geographically) (Table 2.16). Comparing the coefficients of the OLS and spatial regression models (Tables 2.15 and 2.16) shows how the direct effects of the independent variables on the dependent variable

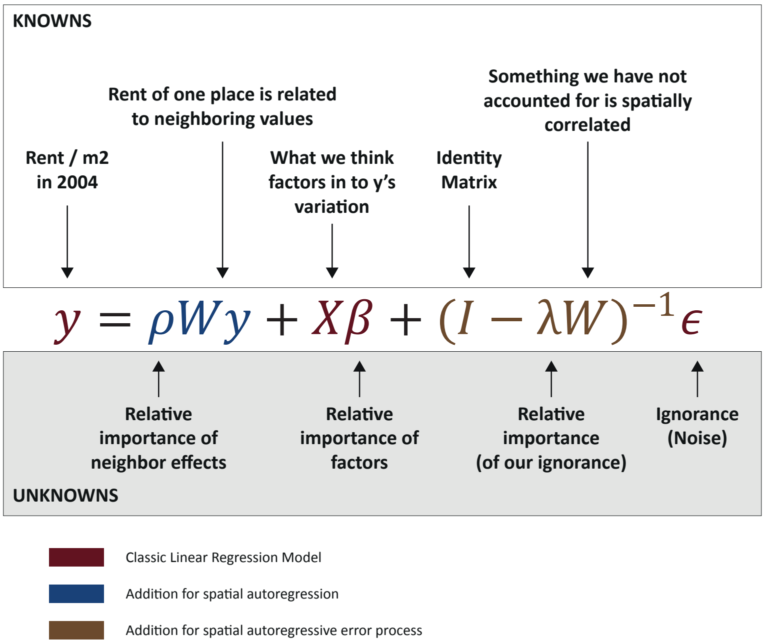


Figure 2.35. The combined spatial and error lag model includes two additional parameters to the common linear regression equation, one for lag (ρWy) and a second for error (I- λW).

Variable	Model 2 (coeff., signif., z-value)			Model 3 (coeff., signif., z-value)		
Constant	1.8413	***	5.7296	1.5792	***	6.1411
Descriptive properties						
Surface Area (m^2)	-0.1429	***	-8.4625	-0.1443	***	-8.6455
Floors below ground level						
Area visible from entry (m^2)	0.0005	***	3.1647	0.0005	**	3.2626
Density of food and retail activities on parcel						
Location is indoors rather than outdoors (bivariate)	0.2936	***	3.1647	0.3302	***	5.3503
Entry is on a street/corridor crossable anywhere (bivariate)	-0.0466	**	-2.8053	-0.0440	**	-2.8771
Configurational categories (Principal Components)						
400m commercial and pedestrian to-movement (PC 1)	0.0768	***	4.42281	0.0623	***	4.4726
100/200m com. to- and through-mvmnt (PC 2)	0.0215	*	2.0497			
800/1600m commercial to-movement (PC 3)	0.0428	**	3.1164	0.0291	**	3.0557
200/400m indoor to- and through-mvmt (PC 4)	0.0208		1.5946			
Pervasive commercial through-movement (PC 5)	0.0433	***	5.4729	0.0457	***	5.9271
Turns avoidance (PC 6)	0.0258		1.8723			
400m housing and treed area avoidance (PC 7)	0.0126		1.1757			
400m park centrality (PC 8)						
Model parameters						
rho	0.3161	*	2.0302	0.3382	***	2.7860
lambda	0.4662	***	4.0379	0.4242	**	3.8718
Fit Statistics						
Spatial Pseudo R2	0.6247			0.6172		

Significance level: *** ρ<0.001, ** ρ<0.01, * ρ<0.05, ~ ρ<0.1

Table 2.16. Model specification for a combined indoor/outdoor (n=1541) spatial lag and error model

Table 2.17. Direct, indirect and total effects of indirect variables on the direct variable (rent per square meter).

Variable	Direct	Indirect	Total
Constant	1.579	0.807	2.386
Surface Area (m^2)	-0.144	-0.074	-0.218
Area visible from entry (m^2)	0.001	0.0002	0.001
Location is indoors rather than outdoors (bivariate)	0.330	0.169	0.499
Entry is on a street/corridor crossable anywhere (bivariate)	-0.044	-0.022	-0.066
400m commercial and pedestrian to-movement	0.062	0.032	0.094
800/1600m commercial to-movement	0.029	0.015	0.044
Pervasive commercial through-movement	0.046	0.023	0.069

are overestimated in the OLS regression, which does not account for spatial autocorrelation in the dependent variable and the error term. For instance, the OLS model suggests that a 1% move towards greater accessibility to pedestrians and outdoor commercial area will provide an 11% increase in rent. This direct effect is the "expected average change across all observations for the dependent variable in a particular region due to an increase of one unit for a specific explanatory variable in this region."[58] This estimation, however, does not consider that such a change for one location would necessarily entail a change on neighboring locations. The spatial combo model accounts for this by incorporating a spatial lag term. In the combo model, the direct effect for the same principal component decreases to 6%. The significant rho (ρ) parameter in model three indicates that spatial interaction occurs among neighboring stores. The total effect of an independent variable on rent per square meter, including the indirect effect a change elsewhere can have on a particular location, can be calculated by including the rho value (here, 0.3382) in the estimation of the coefficient.[59] For the first principal component, the total effect on rental value per square meter for a 1% increase in combined access to outdoor commercial space and pedestrians will be 9%, meaning that there is a 3% increase from indirect effects or a feedback from the same increase among neighboring locations.[60]

Looking at the direct, indirect and total effects for the independent variables in the model, shows that a *decrease* in surface area by 10% leads to an average 1.4% increase in rent per square meter (Table 2.17). To this can be added the indirect effect of 0.7%, which represents the change in rent per square meter arising from a one unit decrease in surface area in another location at a maximum of 400 m (the size of the weights matrix). The total effect, if all locations in an area decreased in surface area would by a 2.2% increase in rent per square meter. The highest total effect is found by being indoors

[58] André Braz Golgher and Paul R. Voss, "How to Interpret the Coefficients of Spatial Models: Spillovers, Direct and Indirect Effects," *Spatial Demography* 4, no. 3 (October 2016): 185.

[59] see Anselin and Rey, *Modern Spatial Econometrics in Practice* section 7.1.4 for one way of calculating spillover effects; and Golgher and Voss, "How to Interpret the Coefficients of Spatial Models" for an alternative way that includes the spatial weights matrix in the calculation.

[60] Neighboring locations here, means 400 meters, which was the minimum distance necessary for capturing at least one neighbor for each location in the spatial weights matrix.

rather than outdoors. If one food or retail location were to become part of the Indoor City, it could see its rent increase by 33% and that of its neighbors (within a 400-meter network radius) by 17%. The combined effect is then an almost 50% increase in rent per square meter. Other variables can be examined in the same way. By increasing by 1% the pervasive centrality at 800 and 1600 m of commercial area, rent per square meter would increase on average by 4%. Such a change would of course require a major restructuring of the road network, but could influence decisions concerning the locations where it would be profitable for property owners to rent space for food or retail activities.

The direct, indirect and total effects are the average impacts that an independent variable may have on rental value in the spatial model. Their impact, however, can vary over the study area. In order to estimate the amplitude, or range, of this impact, the regression equation (see Figure 2.35) can be solved by placing one independent variable at its maximum and minimum values with all other independent variables at their mean. Because spillover effects are accounted for in the inclusion of the spatial multiplier (ρ), the coefficient modeled is the total effect geographically weighted using the weights matrix (W).[61] Also, because the variables that indicate whether the food or retail location is indoors or on a street or corridor that can be crossed anywhere are either zero or one (and therefore cannot logically be situated at a mean value), the amplitudes are reported for three alternatives: for outdoor locations on a street that is not easily crossable, indoors (and of course on a crossable corridor), and outdoors but on an easily crossable street (Table 2.18). This separation also shows some general differences between indoors and outdoors and highlights the indoor advantage in terms of rent per square meter. When all values of the independent variables are at their mean, the rent per square meter of indoor locations is between

Variable	Outdoor locations on non-crossable streets		Indoor locations		Outdoor locations on crossable (pedestrian-friendly) streets		Range of amplitude in percentage around mean
Mean Value ($ CDN)	98		264		84		
	Min	Max	Min	Max	Min	Max	± Mean (%)
Surface Area (m²)	27	207	73	561	23	178	-72–113
Area visible from entry (m²)	79	139	215	376	68	119	-19–43
400m commercial and pedestrian to-movement	65	179	176	485	56	154	-33–84
800/1600m commercial to-movement	72	123	195	332	62	105	-26–26
Pervasive commercial through-movement	58	213	156	576	49	182	-41–119

N.B. On average in 2004, one Canadian Dollar was about 0.77 US Dollars.

Table 2.18. Amplitude of total effects of independent variables in Canadian dollars (2004).

[61] Anselin and Rey, *Modern Spatial Econometrics in Practice* provide a useful discussion on this in sections 7.1.4 and 11.1.1 (where we see that the lambda coefficient does not need to be taken into consideration).

two and three times that of outdoor locations, whether on easily crossable streets or not.

The amplitude of the impact of surface area on rental value is the largest of the independent variables, varying from 72% below the mean value to 113% above the mean value. For indoor spaces, this translates to a value of 73 $ CDN per square meter for the *largest* surface area (of 21,783 m^2) and 561 $ CDNper square meter for the *smallest* (of 6 m^2) (reflecting the inverse relationship between surface area and rent per square meter). For outdoor spaces (which on average rent for less per square meter), the amplitude ranges from 27 to 207 $ CDN and 23 to 178 $ CDN per square meter (for food and retail locations on easily crossable streets). As the differences for outdoor locations of being on a crossable street are not great, only the results of locations of non-crossable streets will be discussed further. The second greatest amplitude can be observed on pervasive commercial through-movement, ranging from 41% below the mean value to 119% above it. For indoor locations that are *not* situated along shortest paths at multiple metric distances between establishments, the rent per square meter is still 156 $ CDN per square meter (with all other variables at their mean). However, when this variable is at its maximum (and the level of pervasive betweenness centrality is at its greatest), rent per square meter increases nearly fourfold to 576 $ CDN. The same amplitude impacts outdoor spaces, although at lower rents per square meter: from 58 $ CDN to 213 $ CDN. This highlights the advantage for stores of being on paths of potentially high foot traffic, not only at a single network radius but pervasively so from 200 to 1600 meters.

For stores situated along streets or corridors that afford little to no access to outdoor commercial area or pedestrians at 400 meters, indoor rents per square meter are on average 176 $ CDN and outdoor rents are 65 $ CDN. Although the increase is lower than for either surface area or pervasive commercial through-movement, when stores are situated at the highest level of accessibility to outdoor commercial area and pedestrians, the value of rent per square meter increases to 485 $ CDN for indoor locations and 179 $ CDN for those situated outdoors. Of the configurational categories, the 800/1600 m commercial to-movement component has the lowest range of impact, only varying by 26% around the mean value. For indoor food and retail establishments with little to no pervasive centrality to commercial area at 800 to 1600-meter network distances, this translates to a rent of 195 $ CDN. The rent per square meter doubles to 332 $ CDN when pervasive centrality goes to its maximum. This increase is less important than that afforded by commercial and pedestrian to-movement or pervasive commercial through-movement. The visibility of the store entry has only a slightly higher overall range of impact on rental values. When visibility is at its minimum (35 m^2 indoors; 1100 m^2 outdoors), a food or retail establishment only rents for about 19 % less than the mean value. At maximum visibility for the sample (20, 480 m^2 indoors; 105766 m^2 outdoors), rent increases to 43% above the mean.

The spatial econometric model reveals not only the range of values of the dependent variable resulting from setting the independent variables at their maximum and minimum values, but can also be used to simulate the marginal effects on rent per square meter of a small change in one of the explanatory variables. A 5% change in each explanatory variables results in increases of rent per square meter of varying magnitude (Table 2.19). For indoor food and retail locations, a 5% *decrease* in surface area would lead to an increase of 9 $ CDN per square meter. For outdoor locations, the same change would only increase rents by 6 $ CDN. Interestingly, a 5% increase in pervasive commercial through-movement, or betweenness centrality at 200 to 1600 m, would increase rents by 18 $ CDN per square meter indoors and 7 $ CDN outdoors—the highest of all explanatory variables. Of course, a change of such magnitude is hard to conceptualize, given the number of centrality metrics that would have to change together. In Eaton Centre, such a change in pervasive betweenness centrality is equivalent to the difference between a store situated on ground level and one situated two floors below ground, where the direct underground connection with other parts of the Indoor City leads to about a 5% higher principal component score than at ground level. A comparable difference on the surface would be the difference between a food or retail establishment situated on Rue Crescent and one situated near the same street but at the intersection with Ste-Catherine, which as an armature in the spatial network tends to harbor a larger proportion of through-movement.

A similar marginal effect occurs for pervasive centrality to outdoor commercial area and pedestrians. A 5% increase in the principal component scores translates to an additional 14 $ CDN per square meter for indoor establishments and 5 $ CDN for outdoor

	Marginal Effects (in $ CDN)		
Variable	Outdoor locations on non-crossable streets	Indoor locations	Outdoor locations on crossable streets
Surface Area (m^2)	6	9	5
Area visible from entry (m^2)	1	3	1
400m commercial and pedestrian to-movement	5	14	4
800/1600m commercial to-movement	3	7	2
Pervasive commercial through-movement	7	18	6

Table 2.19. Marginal effects on rent per square meter of a 5% increase or decrease in the independent variables.

establishments. Outdoors, a 5% increase could be the movement of a store from the middle of a street segment to the nearest busy street (such as Ste-Catherine), where there is a greater accessibility to pedestrians at 400 m. For indoor locations, the same increase is equivalent to the movement of a store on one floor to another or closer to an exit. However, given the absence of pedestrian counts for corridors of the Indoor City, only the relationship to outdoor pedestrian counts and commercial area is accounted for. A 5% increase in 800 and 1600-meter commercial to-movement provides and additional 7 $ CDN for indoor food and retail locations and 3 $ CDN for outdoor spaces. This is equivalent, for example to the difference in Complexe Desjardins between a store situated on a side corridor and one that opens onto the main atrium space.

2.7.2. Spatial variations in the impact of configuration: Geographically weighted regression

The spatial econometric model, despite its ability to account for spatial relationships (with the spatial weights matrix) and spatial heterogeneity (with the rho and lambda parameters), remains a representation that is fixed over space. The calibration process attempts to fit a linear function to the entire dataset, taking the line as an abstract universal form of a significant relationship, defining deviation from the line as 'error' or 'residual'. Spatial phenomena tend to vary over space and it would be expected that the contribution and significance of the contribution of the independent variables would also vary over space. In geographic statistics, a nonlinear approach to spatial regression modelling is the geographically weighted regression (GWR). Rather than correct for spatial heterogeneity with lag and error parameters generated in combination with a spatial weights matrix, a GWR fits a regression function to each element based on its location in the network. It is a technique that "lets the data speak for themselves."[62] More concretely, this means that the model results in an array of equations, one for each element in the analysis. Because the coefficients and the tests of their significance vary per element, they can be mapped and the specific geographic impact of each independent variable, as well as the residuals (the 'error') can be investigated. For this reason, GWR is more interesting than simply accounting for spatial heterogeneity using dummy variables, which tends to rely on pre-existing territorial divisions (abstract universals) or on spatial categories that may be hard to quantify.

The original set of variables contained in the second model of the spatial econometric combo model was placed in a geographically weighted regression using the GWR4 software.[63] The second model was preferred because it includes almost all of the principal

62 Chris Brunsdon, Stewart Fotheringham, and Martin Charlton, "Geographically Weighted Regression—Modelling Spatial Non-Stationarity," *Journal of the Royal Statistical Society. Series D (The Statistician)* 47, no. 3 (1998): 431–43.

63 Tomoki Nakaya and Stewart Fotheringham, *GWR4*, version 4.09 (Chicago, IL: GeoDa Center for Geospatial Analysis, 2016), https://gwrtools.github.io/.

Variable	Coeff. Min	Lower Quartile	Upper Quartile	Coeff. Max	Coeff. Range	Signif.
Constant	1.9921	2.4784	2.7582	3.4811	1.4890	***
Descriptive properties						
Surface Area (m²)	-0.3464	-0.2405	-0.1534	0.0109	0.3573	***
Area visible from entry (m²)	-0.0009	0.0003	0.0010	0.0022	0.0031	***
Location is indoors or outdoors (bivariate)	-0.4709	0.2651	0.4774	0.9177	1.3886	***
Entry is on a street/corridor crossable anywhere	-0.6877	-0.1105	0.0122	0.1840	0.8717	**
Configurational categories (Principal Components)						
400m pedestrian/outdoor area	-0.0387	0.0495	0.1214	0.4133	0.4520	***
100/200m indoor/outdoor area	-0.1114	0.0008	0.0416	0.1290	0.2402	***
800/1600m area centrality	-0.1188	0.0460	0.1131	0.3727	0.4915	***
200/400m indoor area	-0.1207	0.0235	0.0657	0.2456	0.3663	***
800/1600m outdoor betweenness	-0.0003	0.0344	0.0769	0.1693	0.1696	***
Turns to commercial area	-0.1073	-0.0081	0.0433	0.1765	0.2838	***
400m housing and tree canopy	-0.1121	-0.0230	0.0484	0.2564	0.3685	***
Local model fit (R2)	0.1792	0.4778	0.6594	0.7984	0.6192	
Global model fit (Adjusted R2)	**0.7114**					

Significance level: *** ρ<0.001, ** ρ<0.01, * ρ<0.05, ~ ρ <0.1

Table 2.20. Geographically weighted regression model (n=1541).

components, which is more interesting for this exploratory exercise. The spatial relationship between the elements used a Gaussian distance-decay. A kernel bandwidth of 64 m was calculated dynamically using iterative simulations by the software. As is shown in Table 2.20, the coefficients vary slightly and in some cases from negative to positive values. Where the spatial econometric model provided only a global representation of model fit, GWR provides a fit for each food or retail location.[64] Fit varies from 18 % (0.1792) to almost 80 % (0.7984) with half of the sample having a fit between 48 % (0.4778) and 66 % (0.6594). Mapping the model fit shows that the independent variables describe best the variation in rental value per square meter between the Place-des-Arts, Complexe Desjardins, Complexe Guy-Favreau axis and the axis from Eaton Centre to the main station, passing through Place Ville-Marie (Figure 2.36). The model does a poorer job explaining this spatial variation of value of locations inside Eaton Centre, Place Montréal Trust and Complexe Les Ailes.

Mapping the model coefficients reveals the distribution and the degree of statistical significance of the impact on the distribution of rental values per square meter. The lack of diagnostics for spatial autocorrelation means the coefficients must be interpreted with care. Interpretation will only look at the seven variables whose impact is greatest over the whole study area in the third spatial econometric model (refer to Table 2.16). The coefficients for location surface area are highest between Rue Mansfield (1) and Rue St-Laurent (2), with the relative significance of this impact slightly higher in the same

[64] However, GWR lacks several of the diagnostics that the spatial econometric models have and is employed here as more of an exploratory tool.

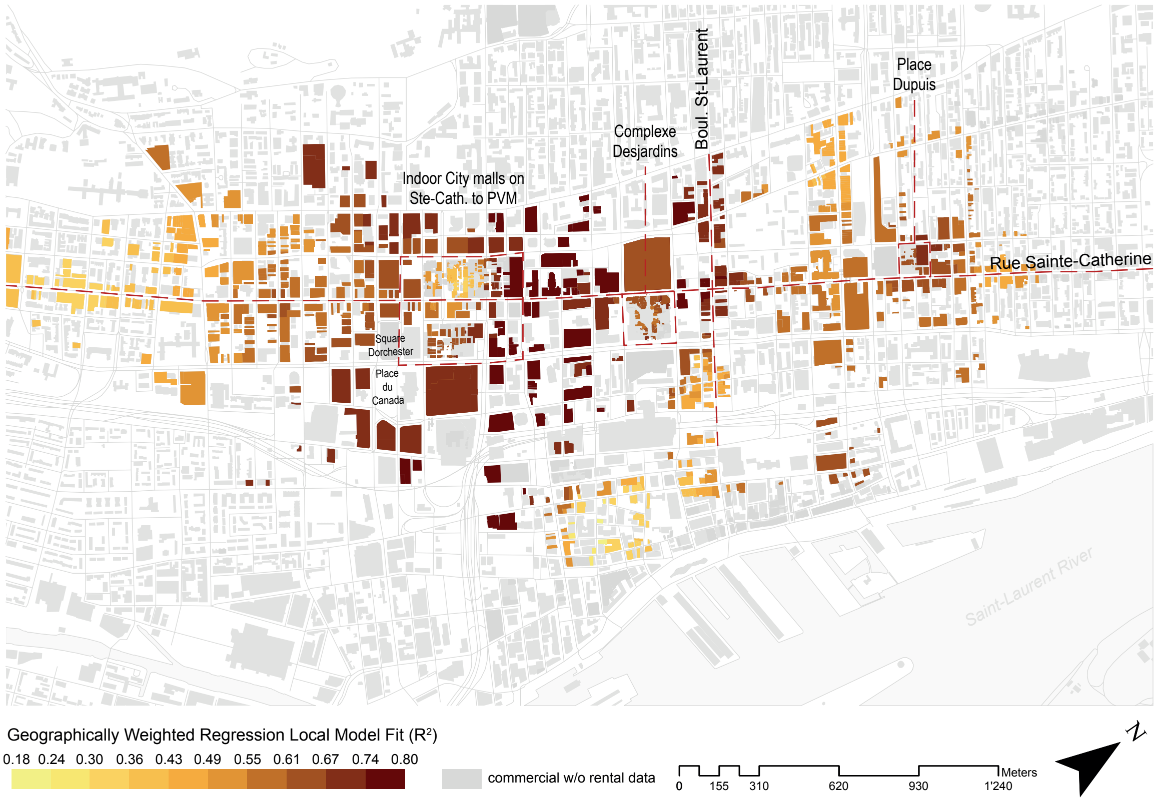


Figure 2.36. Local model fit of geographically weighted regression (n=1541).

area but mostly for outdoor locations (Figure 2.37). The impact of visible area on rental values per square meter is highest in particular around Place Émilie-Gamelin near Place Dupuis (Fig. 2.38, 1) and inside the part of the Indoor City bordering Ste-Catherine (from Place Montréal Trust to Place de la Cathédrale) (2). The relative significance of this impact is highest for the area around Place Émilie Gamelin (1) and includes very few indoor establishments. It is interesting to note that in a couple places, the coefficients are negative (e.g. part of Place Ville-Marie), but that in general for both the indoors and outdoors being more visible for food and retail locations has a positive impact on rental values. The difference between the limited visibility in the indoors and the larger visibility in the outdoors is therefore likely to be more a question of scale than of a radical change in logic (that could have otherwise been heterotopic).

Of the configurational categories, three were significant in the final spatial econometric model. Being centrally located to pedestrians and commercial area at 400 meters provides the largest gains in terms of rental value for both indoor and outdoor locations. The map of degree of similarity to the configurational category (Figure 2.14) revealed that most places with high centrality are found along Rue Ste-Catherine around the Eaton Centre to Place Ville-Marie axis. Mapping the GWR coefficients suggests that the impact of belonging to this configurational category has a positive effect on rental values for both this same area as well as most of the

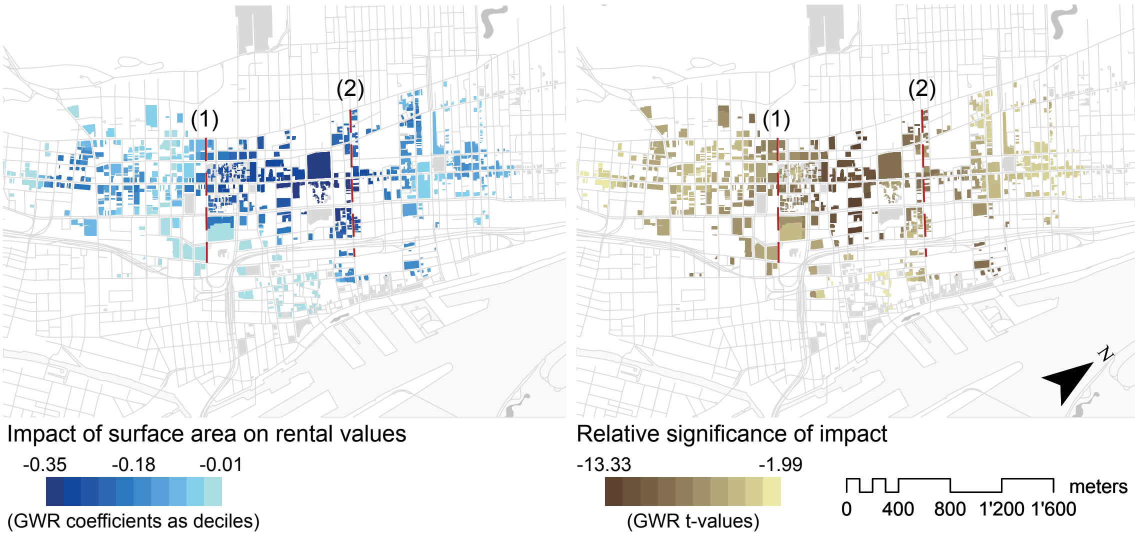


Figure 2.37. GWR coefficients for the impact of surface area on rental values and the relative significance of impact. Impact the significance of this impact are highest between Rue Mansfield (1) and Rue St-Laurent (2).

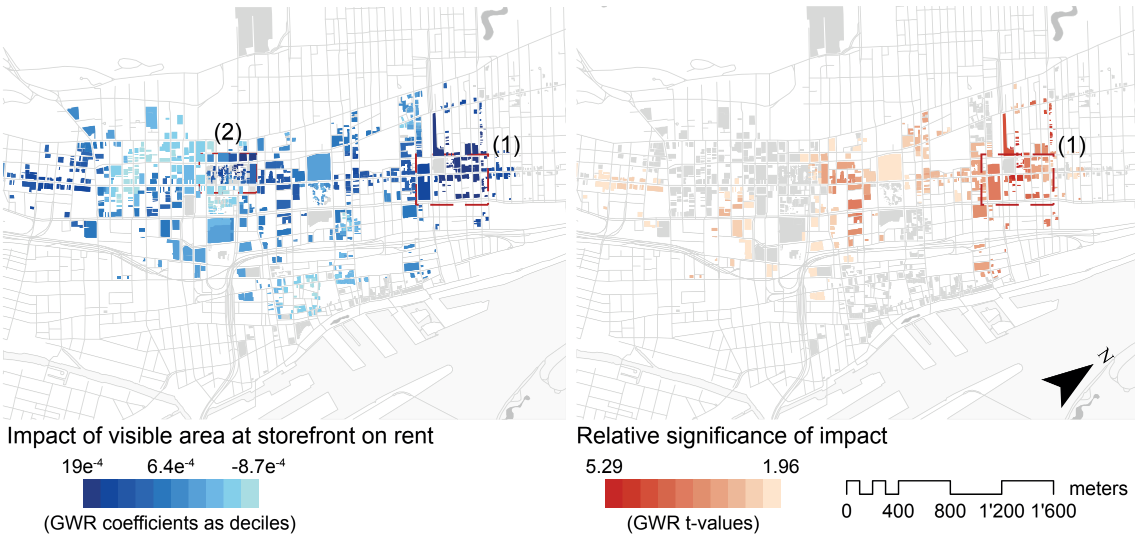


Figure 2.38. GWR coefficients for the impact of visible area at storefront. With highest impact around Place Émilie-Gamelin near Place-Dupuis (1) and around part of the Indoor City from Place Montréal Trust to Place de la Cathédrale.

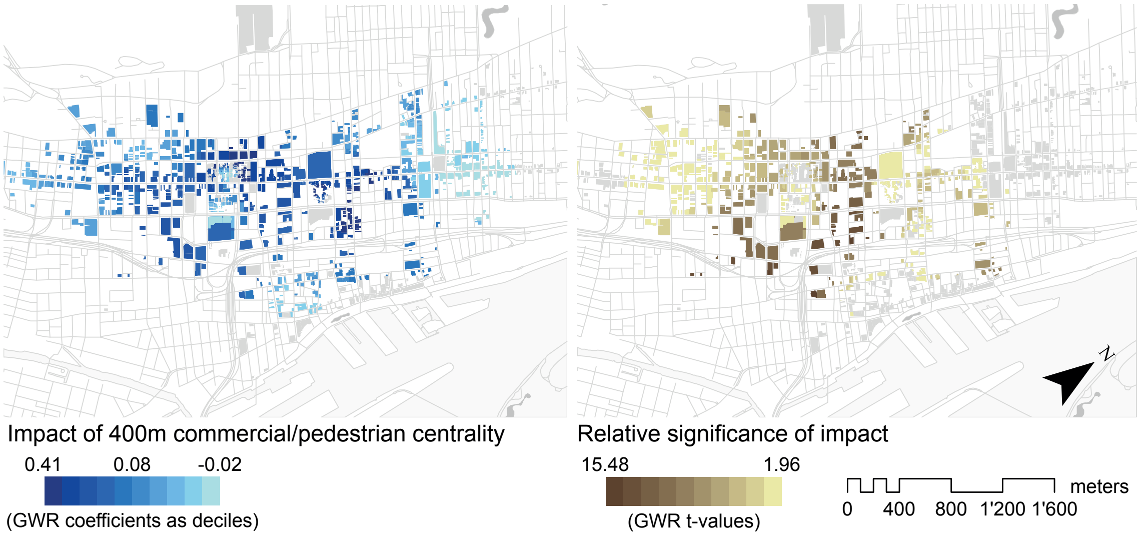


Figure 2.39. Impact on rental values of being centrally located to outdoor pedestrians and commercial area at 400 meters

rest of the study area (Figure 2.39). The significance of the impact of the coefficients on rental value, however, tends to be higher around the indoor city without including it. This is not surprising given the fact that the pedestrian counts were limited to the outdoors and the Indoor City is an important origin and destination for pedestrian travel.

Pervasive betweenness (mostly) positively impacts rental values and, as the evaluation of marginal effects suggests, would have the highest impact if increased by 5%. As was apparent in the map of the distribution of degree of membership to this configurational category (Figure 2.18), the betweenness metrics tends to emphasize the main commercial streets in the Montreal downtown. It indicates how the significance of the impact tends to include more outdoor locations than indoor locations when coefficients are allowed to vary geographically. The continuity and intensity of commercial area on Ste-Catherine (1) means that the rental value per square meter of establishments at several intersections from east to west are positively influenced by high pervasive betweenness centrality (Figure 2.40). This is particularly true for the cross-streets of St-Denis (2), St-Laurent (3, with Chinatown apparent to the south), Rue Crescent (4) and part of the Indoor City near Promenades de la Cathédrale (5). The positive (and significant) impact of betweenness on this part of the Indoor City is likely due to the fact that it is directly connected to many locations underground as a direct thoroughfare to the metro and has dedicated entries that are well-indicated at street level (Figure 2.41).

The 800/1600 m commercial to-movement configurational category has the smallest impact on rental values, both in terms of total as well as marginal effect. It also has the smallest range of impact. In the GWR, it turns out to be of lowest significance, which is curious because it was among the most significant contributors to rent variation in both the original OLS model and the spatial

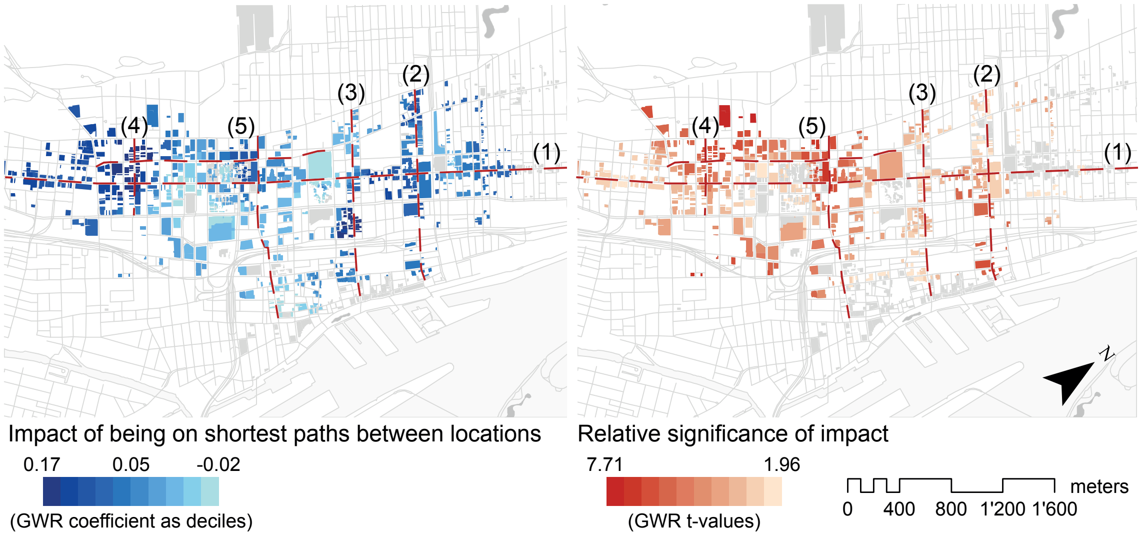


Figure 2.40. Impact on rental values of being situated on shortest paths between commercial locations weighted by surface area.

Figure 2.41. https://upload.wikimedia.org/wikipedia/commons/6/65/Promenades_Cathedrale_9.jpg

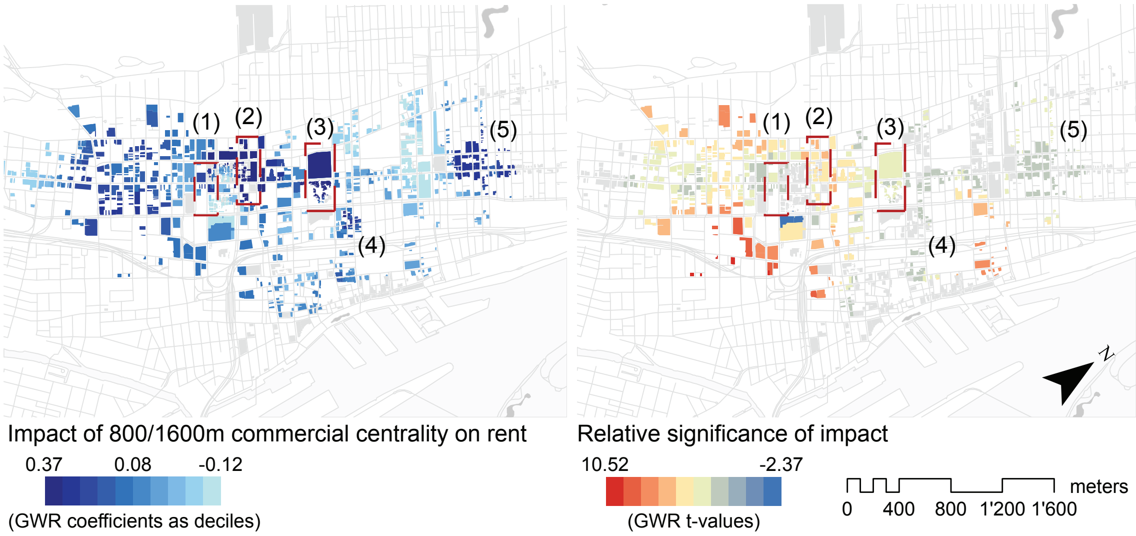


Figure 2.42. Impact on rental values of being pervasively central to commercial area at 800 and 1600m

econometric combo models 2 and 3. The impact indicated by the GWR is concentrated in food and retail locations along Ste-Catherine southwest of Eaton Centre (Figure 2.42, 1) and in stores in Place de la Cathédrale and outdoors along Avenue Union northwest towards Rue Sherbrooke (2). The rental values of Complexe Desjardins and the Place des Arts are positively and significantly affected by commercial to-movement at 800 and 1600 meters. The rental values of stores around Chinatown (4) and Place Dupuis (5) are highly impacted by this aspect of their spatial configuration, but the relationship does not appear to be highly significant.

2.8. Chapter summary and conclusion

This chapter explored the Montreal downtown as a volumetric economy of avoidance and encounter that includes outdoor and indoor food and retail locations. In contrast to previous studies, the indoor spaces were conceived as part of a single spatial model incorporating indoor, outdoor, aboveground and belowground locations. The Montreal Indoor City is an interesting case because it is well documented and has been extensively studied—but never in its relationship to neighboring outdoor spaces. It is also a paradigmatic example of urban underground space and so any analysis conducted of Montreal should be able to be conducted elsewhere. The results would likely not be the same, but the underlying mechanisms of encounter and avoidance might share some similarities in other cities like Hong Kong or Helsinki.

The spatial network model of the downtown was conducted in ArcGIS, which made including other georeferenced data relatively easy. Rather than limit the centrality measures to corridors, as previous studies adopting the Space Syntax approach have done, the use of the Urban Network Analysis Toolbox permitted the calculation of centrality for each food and retail entry point. The metrics adopted were gravity, straightness, betweenness and turns.

The data provided by the Observatory on the Indoor City (OVI) at the University of Montreal, which maintains a two-dimensional representation of the store locations in the Indoor City, made it easier to both locate store entry points indoors and attribute certain characteristics to each. The floor plans of the indoor locations also made locating and building the indoor paths easier. The paths both indoors and outdoors did not rely on street centerlines, which were too general for representing pedestrian movement, but rather relied on axial lines computed in Space Syntax's DepthMap. By placing barriers to pedestrian movement, shortest paths through convex spaces like squares or indoor central areas helped reduce the number of possible paths in such spaces to the most direct ones.

The centrality analyses revealed that in terms of to-movement (gravity and straightness), indoor and outdoor locations tend to cluster in ways that suggest that they are engaged in a mutually beneficial spatial interaction. The through-movement (betweenness and turns) metrics highlight the linearity in the network and the well-known commercial streets of Ste-Catherine, St-Laurent and St-Denis. Although outdoor locations tend to be located on the shortest paths *between* a larger food and retail surface area, the Indoor City also has particular corridors through which most origin-destination pairs pass, in particular from Eaton Centre, where corridors from Place Montreal Trust and Complexe Les Ailes meet and descend underground to Place Ville Marie. The subtlety in what centrality metrics reveal about the relationships between places questions the common dichotomy of indoor and outdoor when spatially analyzing commercial spaces.

The tendency for centralities to occur at multiple scales–for there to be multiscalar pervasive centralities and peripheralities (being 'segregated' at multiple scales)–was addressed by placing the forty-four spatial metrics in a principal component analysis (PCA), which allowed each location to receive a PC score representing a degree of membership to a spatial configurational category. This form of categorization has the advantage over cluster analysis of not forcing elements into single or predefined classes. As such, the approach avoided the common typomorpholocial use of abstract universals in favor of concrete universals—categories that emerge from the dataset itself. The resulting components identified a common relationship between accessibility to pedestrians and to commercial area at 400m. There also did not appear to be any major configurational differences between the inside and the outside, except in the pervasive betweenness metrics which tended to characterize less the indoor locations when transformed into principal components.

The data provided by the OVI contained 2004 Rental Roll data, which meant that it was possible to evaluate how spatial configuration contributed to variations in rental value per square meter in the spatial network. As opposed to the use of spatial statistics in other studies on spatial configuration (with only a few exceptions), the analysis did not rely on simple linear regressions with no diagnostics for spatial collinearity or heterogeneity, but rather adopted methods common to spatial econometrics. It is common for the distribution of spatial phenomena to be heterogeneous. This was the case for rental value in Montreal, and the spatial relationships between the food and retail locations had to be accounted for using a spatial weights matrix. The results from the spatial econometric model for the whole study area (1541 locations) suggests a positive relationship between rental value per square meter and the amount of commercial surface area and number of pedestrians accessible at 400 m (or a 5-minute walk). Also significant were the proximity of commercial area at 800 and 1600 m and to only locations at 200 to 400 meters. Rental values per square meter are in general higher indoors than outdoors and for smaller stores than larger ones.

Where the spatial econometric model generalized the impact between spatial configuration and the distribution of rent value in the Montreal downtown, spatial heterogeneity of impact was explored further using a geographically weighted regression (GWR). As opposed to spatial econometric models that fit the data to a single linear relationship, GWR fits a regression model to each food and retail location, allowing the fit and coefficients to vary geographically. Mapping the fit showed that in general the spatial configurational variables described more than 50% of the variance in rental values across the whole model. Spatial configuration tends to contribute positively to rental value per square meter across the Montreal downtown, both indoors and outdoors, but to different degrees and with varying levels of significance.

As mentioned in the beginning of the chapter, the regression model serves to produce a particular spatial mechanism in order to see how it works. As a model, it remains only an approximation of the dynamics occuring in downtown Montreal between the indoor and outdoor food and retail locations. The configurational categories, it should be reminded, are specific to this dataset as concrete universals and therefore cannot be applied directly to other urban fabrics. Similarities may exist, even in the impact that certain configurational categories will have on rental values elsewhere, but the proportions of these relationships will vary and some may be significant elsewhere that are not so here. However, the method employed here could easily be applied elsewhere and comparisons made, particular between configurational categories.

The investigation here looked at the specific economy of encounter and avoidance of food and retail locations. Further work on Montreal could extend the analysis to include service and cultural activities in the model. The accessibility metrics could be multiplied with additional data and a richer set of configurational categories could be produced. The use of multiple spatial metrics avoids taking a position on the most important metric in describing pedestrian movement. However, the many possible ways of navigating the urban volume of Montreal may merit in situ investigation using commented walks or by tracking people's movements using GPS. The recording of actual movements with times spent in certain parts of the downtown, both indoors and outdoors, would help compare an analysis of potential movement using spatial configuration with one of actual movement using dynamic pedestrian data.

The following chapters will not look at urban spatial configuration with this same level of detail. The analysis of Montreal evolved in parallel with the three case studies mapping underground potential. In each, the potential of the urban form to support underground space is evaluated differently. The analysis of Montreal is less the end to the investigation of urban potential for underground spaces and more a starting point for future work on the economy of encounter and avoidance of the urban volume.

Chapter 3.0

Mapping Underground Potential

3.0.1. Introduction

This chapter presents three cities where the Deep City method was conducted: San Antonio, Texas, Hong Kong, China and Dakar, Senegal. Before delving into each case study in detail, this introductory section will briefly present the procedure for mapping underground potential, with particular attention given to the grouping of geological formations into geotypes, the Analytic Hierarchy Process for developing relative scales using priority vectors and the calculation of the maps with Order-weighted Averaging, which accounts for attitudes towards risk in the aggregate process using fuzzy qualifiers. The conditions and circumstances that led to the choice of the three cities will also be discussed.

3.0.2. The Deep City Method

Underground potential is mapped in three main steps (Figure 3.0.1). First, the current underground and surface conditions are modelled in a geographical information system (GIS). The necessary information can be as simple as only geological maps in as many depths as made available. Often, there is a map of superficial geology (more recent surface geology) and another of the substrate (older formations). When these maps are not digitized, they have to be done so by hand or using an algorithm available in software packages like ESRI's ArcGIS. When possible, information concerning groundwater heights, ground temperatures and existing underground infrastructure can be included. In order to account for the existing urban morphology, street centerlines are required, and building footprints or parcels can help qualify the latent potential of the urban form using centrality metrics. More data is better, but it is not necessary. The scale of the maps produced provides a general overview of underground potential that should be verified later

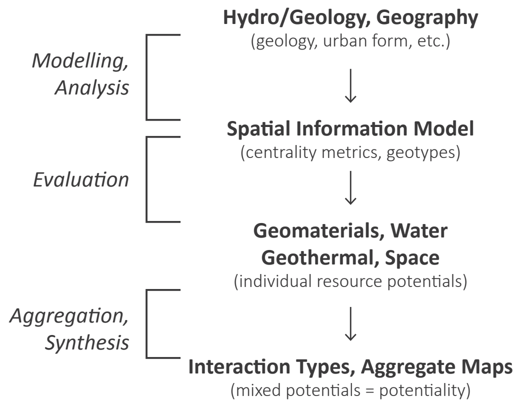


Figure 3.0.1. Deep City mapping procedure main steps (adapted from Parriaux et al 2010).

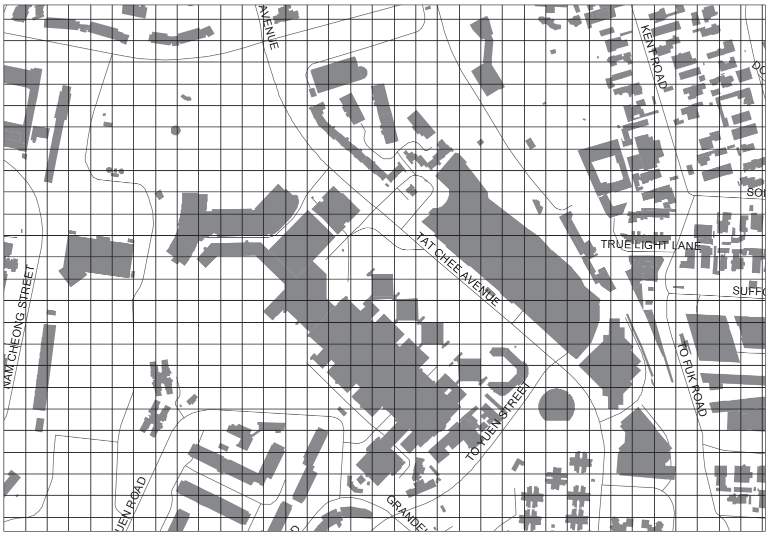


Figure 3.0.2. Example of extract of the 25x25 grid produced for Hong Kong. Each cell contains the data compiled in the geo-database.

with site investigations. A long list of necessary data would make it impractical for many cities to conduct the Deep City process.

Each layer of information is converted to a raster dataset using a common cell size. The grids of Hong Kong and Dakar, for instance have a cell size of 25 meters by 25 meters. For San Antonio, due to its size (which impacts computation time), a grid of 50 x 50 meter cells was used. Figure 3.0.1 illustrates the way the grid is posed over the territory. The advantage of the grid is its being able to account for different types of data collected at different scales. Other types of territorial divisions (parcels, planning units, street blocks) are less useful in that they are pre-existing political divisions that do not cover the map in a homogeneous manner. This approach therefore differs from previous underground maps where parcels have been used or where the underground has been bounded in areas according to geological or topographical conditions.[1] The grid's being a vector

[1] for examples of reporting underground potential on parcels, see Huanqing Li et al., "An Integrated Planning Concept for the Emerging Underground Urbanism: Deep City Method Part 2 Case Study for Resource Supply and Project Valuation," *Tunnelling and Underground Space Technology* 38 (September 2013): 569–80; Zhongle Lu et al., "Quantitative Assessment of Engineering Geological Suitability for Multilayer Urban Underground Space," *Tunnelling and Underground Space Technology* 59 (October 2016): 65–76; Jian Peng, Yang Wang, and Fangle Peng, "Evaluation of Underground Space Resource for Urban Master Plan in Chanzhou City," in *Underground Space: Planning, Administration and Design Challenges* (ACUUS 2014, Seoul, South Korea, 2014), 30–35. The Helsinki and Hong Kong master plans designate areas of underground potential as zones Ilkka Vähäaho, "An Introduction to the Development for Urban Underground Space in Helsinki," *Tunnelling and Underground Space Technology* 55 (May 2016): 324–28.

file also means that all the relevant data are contained in a single database. Raster datasets can only contain a couple fields, which multiplies the number of places data is stored.

3.0.2.1. Geotypes: Families of geological formations

While the datasets are compiled in the grid file, the geological formations are grouped into geotypes. Geotypes are both intended for urban planners who are not accustomed to working with geological formations and in order to facilitate quick comparisons by geologists with other contexts having the same geotypes. The grouping process can be performed by geologists familiar with the behavior of certain geological formations, according to their genealogy (Quaternary, Mesozoic, etc.) and sedimentology (petrographic/mineral qualities). These same qualities serve as a basis for evaluating the potential for the different geotypes to contain groundwater, conduct heat (for geothermal energy), support foundations of buildings or infrastructure, or provide geo-materials (minerals, etc.) that may be of use in the local or regional market.[2]

3.0.2.2. The Analytic Hierarchy Process: Calculating relative scales of suitability locally and globally

The second step evaluates the relative suitability of the geotypes for each resource. It is this suitability that constitutes its potential for particular uses, based purely on the characteristics of the geology and independent of needs or other constraints such as cost or political and social aspects. Suitability is quantified using the Analytic Hierarchy Process.[3] Rather than rate, for example, the suitability for foundations of each geo-type on an ordinal scale (e.g. 1-10), the geotypes are compared pairwise according to linguistic qualifiers (e.g., 'A and B are of identical suitability', 'A is moderately more suitable than B', 'A is much more suitable than B', etc.) in order to develop a relative level of priority. The linguistic qualifiers are given numbers, usually from 1 to 9, with one equivalent to equal suitability and nine representing the opposite extreme, where one element is significantly more suitable than another.[4]

The suitability of each element is quantified by placing the results of the pairwise comparisons in an n by n matrix (where n is the number of elements or geotypes in this phase of the mapping). The matrix is normalized and solved to produce a principal eigenvector, which situates the relative suitability of each geotype between zero and one. An of the AHP is its ability to verify the consistency of the results of the pairwise comparisons. In some cases, the relationships between geotypes may not obey the law of transitivity (that the

[2] A. Parriaux and Pascal Turberg, "Les Géotypes, Pour Une Représentation Géologique Du Territoire," *Tracés* 133, no. 15–16 (2007): 11–17.

[3] Thomas L. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation* (New York ; London: McGraw-Hill International Book Co, 1980); Alessio Ishizaka and Ashraf Labib, "Review of the Main Developments in the Analytic Hierarchy Process," *Expert Systems with Applications*, May 2011.

[4] The scale of 1 to 9 is recommended by Thomas L. Saaty, "How to Make a Decision: The Analytic Hierarchy Process," *European Journal of Operational Research* 48, no. 1 (September 1990): 9–26.

relationship between A and C is consistent with the relationship between A and B and B and C). The AHP provides a consistency score that measures the degree of lack of transitivity in the matrix. Generally, inconsistency below 10% is acceptable. Inconsistency above 10% should be investigated in order to find out between which elements this inconsistency lies.

For each of the case studies, the pairwise comparison process and production of the suitability vector using the comparison matrix will be presented and will demonstrate in more detail the method, with slight differences in its application and adaption in each case study. The AHP remains a popular tool for the production of relative scales. These scales are often called 'priority vectors', because they are used in decision-making aids. Pairwise comparisons are being used to weigh alternatives in order to pick the 'best' and only one. That is not the main use of the AHP here, where relative scales establish the relative suitability and capture the tacit knowledge of local experts. One location is more suitable than another and when considering resources separately, the vector would be synonymous with priority, or the 'better' place to construct underground space and extract groundwater or geomaterials. Here, the combination of this suitability means looking at these only as potentials. The vectors together constitute a potentiality.

3.0.2.3. Order-Weighted Averaging: Aggregating criteria according to attitudes towards risk

The third and final step in the Deep City method establishes a set of criteria in addition to the geotypes, aggregates them to produce a map of a single resource potential and then further aggregates the four resources to form a combined map of potentiality. This aggregation process, particular for the AHP has received quite a bit of attention. As opposed to only adding each normalized criteria weight, Yager and Kelman propose using fuzzy qualifiers in the AHP.[5] These qualifiers address the relative importance of the strongest and weakest criteria in their aggregation process by first ordering the criteria weights (the suitability vector) from highest to lowest and then multiplying them by an order weights vector. This order weights vector can place the emphasis on either the strongest criteria, whichever are the most suitable, or on the weakest (whichever have the lowest potential). This former, emphasizing the strongest weights, approximates a risk-taking attitude of the evaluation process where the highest resource potential or criterion is considered 'good enough' and the evaluator is optimistic about the ability to deal with the weakest resource potentials. The latter, weighing according to the weakest criteria simulates a risk-averse situation where the weakest potentials or criteria influence the

[5] Ronald R. Yager and Antoine Kelman, "An Extension of the Analytical Hierarchy Process Using OWA Operators," *Journal of Intelligent and Fuzzy Systems* 7 (1999): 401–17.

overall potentiality or suitability.[6] The aggregation process produces a single map, which represents potential as a single quantity. However, this is not always easy to interpret, without stepping backwards in the aggregation process. This dissertation, particularly in the San Antonio and Dakar case studies will investigate an alternative method by which combined potentials are addressed as interaction types, which capture the degrees of overlap of each of the resource potentials in a series of maps.

3.0.3. Selecting Case Study Cities

As the examples of Paris and Mexico City given in chapter 1 illustrate, groundwater poses one of the greatest challenges to a city's relationship to its underground resources, particularly when an urban aquifer provides the main source of drinking water for the region.[7] Unlike geological materials (the exploitation of which has only a limited geographical impact) groundwater extraction or pollution have consequences that can reach a much larger scale.[8] According to the World Hydrogeological Map at least 122 cities around the world with a population of greater than 1 million obtain at least 25% of their total water consumption from groundwater.[9] Verifying each of these cities individually using information from local and national organizations, reveals that at least 50 rely on an urban aquifer for more than 50% of their drinking water (Figure 3.0.3).

Most studies on the urban underground tend to be in cities where there is already a significant amount of underground infrastructure (Paris, Berlin, Helsinki, Montreal, Toronto), where there have been conflicts between resources (Paris, Mexico City), or where necessity is already fueling a hasty investigation of the subsurface opportunities (Hong Kong, Hanoi). The 'resources to needs' paradigm of Deep City is less interested in places where necessity has already oriented planning processes at the expense of opportunities or conflicts. Furthermore, the importance of investigating synergetic multiple uses of the underground means that a city where there is only one resource potential is less interesting for pushing the mapping method further. For this reason, the cities of San Antonio and Dakar were chosen for their complicated relationship to their drinking water source, the majority of which is situated, in both cases, beneath the city. San Antonio is also in North America, a continent where urban underground potential has received less attention in recent decades due to the lack of demographic booms and rapid development that are impacting cities in Asia and Africa. The availability of land,

6 For a precise mathematical description, please see Soheil Boroushaki and Jacek Malczewski, "Implementing an Extension of the Analytical Hierarchy Process Using Ordered Weighted Averaging Operators with Fuzzy Quantifiers in ArcGIS," *Computers & Geosciences* 34, no. 4 (April 2008): 399–410.

7 Pascal Blunier, "Méthodologie de Gestion Durable Des Ressources Du Sous-Sol Urbain" (Doctoral Dissertation, EPFL, 2009), http://library.epfl.ch/theses/?nr=4404.

8 B. L. Morris et al., *Groundwater and Its Susceptiblity to Degration a Global Assessment of the Problem and Options for Management* (Nairobi, Kenya: Division of Early Warning and Assessment, United Nations Environment Program, 2003), http://www.unep.org/DEWA/water/groundwater/pdfs/Groundwater%5FINC%5Fcover.pdf.

9 Wilhelm Struckmeier and Andrea Richts, "Groundwater Resources of the World," Electronic Map (Hannover: BGR/UNESCO, 2008).

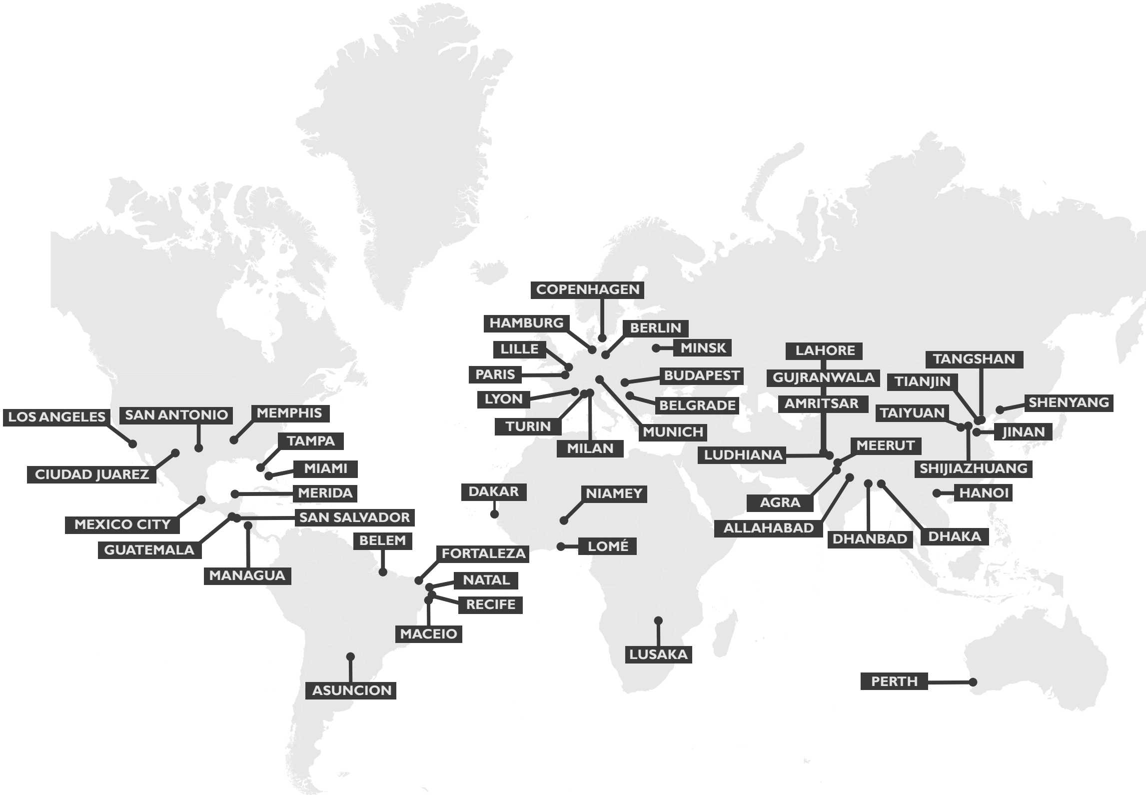


Figure 3.0.3. 50 world cities rely on an urban aquifer for more than 50% of their drinking water.

however, is countered by urban planning policies encouraging more compact forms of developing, increasing density and the mix of activities. The urban volume may be a source of potential synergy or conflict in this process of intensification.

Unlike North America, where population growth is stagnant and developable land is abundant, Africa is a continent with some of the highest population growths anywhere in the world, fueled both by birth rates and migration to urban areas. While some cities may have plenty of land to expand and fewer policies resisting sprawl, the city of Dakar in Senegal is located on a peninsula. Not only does the city have little land to expand, a major aquifer is situated beneath most of the developed areas of the city and is the source of both synergy (water for drinking and irrigation) and conflict (flooding, pollution). Although the city has not looked extensively at underground options, either for building space or harnessing alternative sources of energy, the underground may constitute a reservoir of untapped potentials.

The city of Hong Kong was chosen through a collaboration with an external partner. When they received the mandate to draw up the cavern master plan, the project leaders from the British engineering firm Arup and Associates organized a duty visit to Switzerland and France in late 2014 for representatives from the the Civil Engineering and Development Department (CEDD) of the city of Hong Kong as well as from the Development, Commerce and Economic Development Bureaus, the Buildings and Fire Safety Departments, the Planning Department and the Government Records Service. The visit to Switzerland included a half-day meeting with the Deep City Project at the Swiss Federal Institute of Technology in Lausanne. The discussions touched on experiences with transforming data into underground potential and with the utility of the maps for the different departments. The case study of San Antonio, already well under way, was presented as an example of evaluating multi-resource potential in a context where the need for the underground was not pressing and the analysis could depart from the resources instead. In contrast to the cavern study, the delegation remarked that Deep City was particularly focused on 'basement' development under existing urban areas. This was something that Hong Kong was interested in exploring further and the delegation felt that Deep City could provide a complementary evaluation to the cavern suitability map.

In order to pursue this opportunity to test the Deep City method on a city where a diagnostic of underground potential was in process, the author organized a three-week visit to the Arup office's in Hong Kong, where he worked with the team drawing up the cavern plans. The objectives written up in collaboration with Arup were to 1) provide Arup with a map of the distribution of underground space potential for the Hong Kong SAR and 2) to estimate possible changes in property values brought about by the permutations of land uses. This second objective proved impractical for the visit, both in terms of time and of the type of data necessary for a spatial econometric analysis of this type. The Hong Kong case study is also an opportunity to test the robustness of the Deep City method in comparison with other methods applied to the same dataset. It helped to identify and reinforce the core principles of Deep City.

The case studies will be presented in the order they were conducted: San Antonio, Hong Kong and Dakar. The objective is not to compare the underground in these three cities (this is not a comparative study), but rather to examine the adaptability of the mapping procedure to different geological, urban and informational contexts.

Chapter 3.1

Deep City San Antonio

3.1.1 San Antonio, Texas: Extractions, Constructions and Transformations

3.1.1.1. Conditions: Geology, Aquifers, Geothermal Energy, Urban Structure

Located in Bexar County in south-central Texas, the city of San Antonio is, as of 2015, the seventh largest in the United States with a population of a little over two million and an average population density of 1100 people per square kilometer.[1] Like many North American cities, its population growth over the next ten years is expected to be around 1% per year[2] and nearly 80% of work trips are made alone in an automobile.[3] Although it is difficult to evaluate cities using such general statistics, it is evident that San Antonio does not display an urgent need for underground space development. Surface land is plentiful enough to support the activities of the population for several years to come. As evidenced by proposals made by the City Design Department[4] and the feasibility studies mandated by the VIA Metropolitan Transit,[5] however, there is an interest in consolidating urban activities and linking them by attractive transportation alternatives to the automobile. Presumably, the lack of extensive underground space development means that certain synergies remain to be explored and conflicts avoided.

1 Demographia, "Demographia World Urban Areas: 12th Annual Edition" (Belleville, Illinois: Demographia, 2016), www.demographia.com.

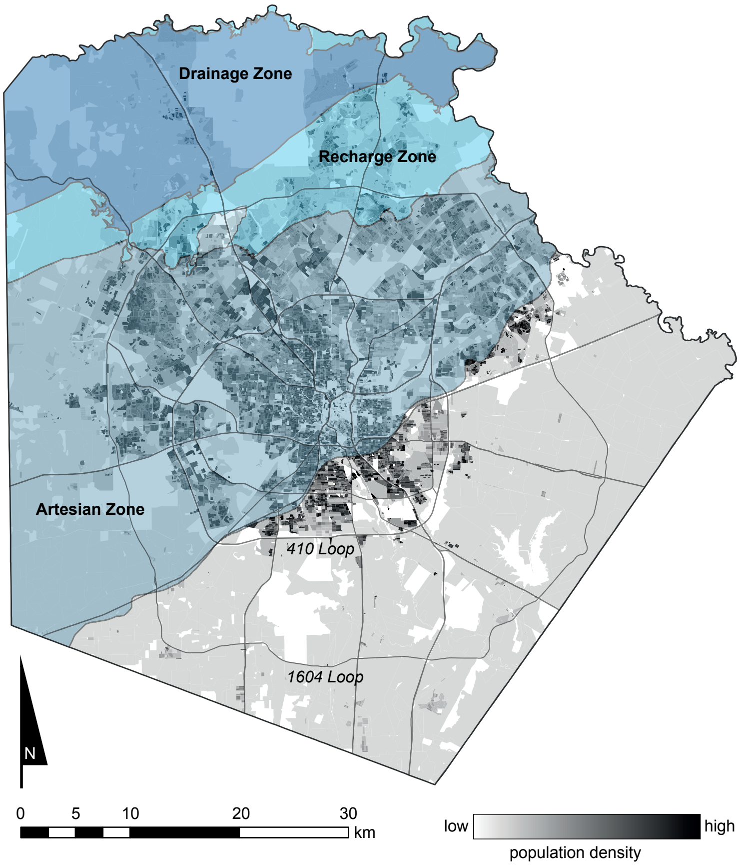
2 Jacobs Engineering, "2035 Long Range Comprehensive Transportation Plan" (San Antonio, TX: VIA Metropolitan Transit, 2011); United Nations Human Settlements Programme, *State of the World's Cities, 2012/2013: Prosperity of Cities* (New York: Routledge for and on behalf of UN-Habitat, 2013).\\uc0\\u8220{}2035 Long Range Comprehensive Transportation Plan\\uc0\\u8221{} (San Antonio, TX: VIA Metropolitan Transit, 2011

3 U.S. Census Bureau, "2014 American Community Survey 1-Year Estimates: Means of Transport to Work by Selected Characteristics," 2014, http://factfiner2.census.gov.

4 San Antonio City Design Center, "Downtown Design Guide (January 7th Draft)," 2014, http://www.sanantonio.gov/Portals/0/Files/CityDesignCenter/DowntownDesignGuide.pdf.

5 Jacobs Engineering, "2035 Long Range Comprehensive Transportation Plan."

Figure 3.1.1. Aquifer zones and the distribution of population densities over Bexar County (data sources: US 2010 Census and the Edwards Aquifer Authority)



To say that San Antonio has no relationship with its underground resources would be to ignore other uses of the groundwater and geological formations. Almost 75% of the city's drinking water comes from the Edwards aquifer system situated beneath most of the city,[6] requiring a rate of extraction that places it on the World Hydrogeological list of 122 cities where overexploitation is a growing risk.[7] Most inhabited areas in Bexar county lie over the artesian and recharge zones of the aquifer (Figure 3.1), the former being the location where water flows naturally without pumping in wells and the latter where rainfall and surface springs feed into the Edwards. A transition zone, which contributes to a lesser degree to aquifer recharge, has been identified by the San Antonio Water Services (SAWS) between the two. The southern border of the artesian zone is determined by the underground infiltration of sea water from the coast. The movement further inland of this line, which threatens the affordance of the aquifer as a source of drinking water, is monitored regularly by SAWS and the U.S. Geological Service (USGS).[8] Above

[6] SAWS, "Semiannual Water Management Report: January-June 2015" (San Antonio, TX: San Antonio Water System, 2015).

[7] Wilhelm Struckmeier and Andrea Richts, "Groundwater Resources of the World," Electronic Map (Hannover: BGR/UNESCO, 2008).

[8] Johnathan V. Thomas, Gregory P. Stanton, and Rebecca B. Lambert, "Borehole Geophysical, Fluid, and Hydraulic Properties within and Surrounding the Freshwater/saline-Water Transition Zone, San Antonio Segment of the Edwards Aquiferr, South-Central Texas, 2010-2011" (Austin, Texas: Texas Water Science Center, 2012).

the Edwards, small locally-confined groundwater resources provide secondary sources of water for irrigation and industrial uses.[9]

San Antonio is situated on the Balcones Fault Zone, which not only structures the Edwards aquifer system, but also explains the variety of geological strata that are visible on the surface. Pervious karstic limestone and granite formations constitute the major geological formations found in the northwest portion of the county, with impervious clay and sand formations making up the geological conditions in the south (Figures 3.1.2 and 3.1.3). The location of the permeable formations coincides with the aquifer recharge and transition zones. Traversing these substrata, and carried mostly by the river systems of the San Antonio, San Pedro Springs and the Leon and Salado Creeks, are a series of quaternary alluvial formations that are around six to fifteen meters deep and coincide in particular with the downtown and the historic neighborhoods of the city. The pattern of urbanization follows the ease of foundation construction afforded by the geology. The expansion of the city northward (in the directions of Kendall, Comal and Guadalupe counties) has occurred mostly over the stable limestone and granite formations, while the tendency for the clay and sand formations to expand and contract renders construction more difficult.[10]

Around Bexar County, the geological formations are extracted and transformed for use as building and construction materials. According to the Texas Mineral Resources Map maintained by the Bureau for Economic Geology, Texas is one of the nation's leading producers of limestone and there are thirteen limestone quarries in the San Antonio-area, according to USGS mine data.[11] The limestone is relatively easy to extract and is used for bulk building materials in roads and concrete aggregates. The sand and gravel formations serve for the construction of roads, sidewalks and building foundations. Much of the asphalt used in San Antonio's roads is locally produced and the clay formations are used for fabricating bricks and cement.[12] The local production of building materials is praised for saving costs in infrastructure and is seen as an important mainstay in the San Antonio economy.[13]

The interactions between urban expansion, water extraction and mineral transformation has led San Antonio to develop important management instruments. The benefits of the synergy identified historically by patterns of settlement and the quarrying of limestone are countered by the need to monitor the quality and quantity of the groundwater available. The groundwater resource is maintained

9 Thomas E Ewing, *Landscapes, Water and Man: Geology and History in the San Antonio Area of Texas* (San Antonio, Tex.: South Texas Geological Society, 2008).

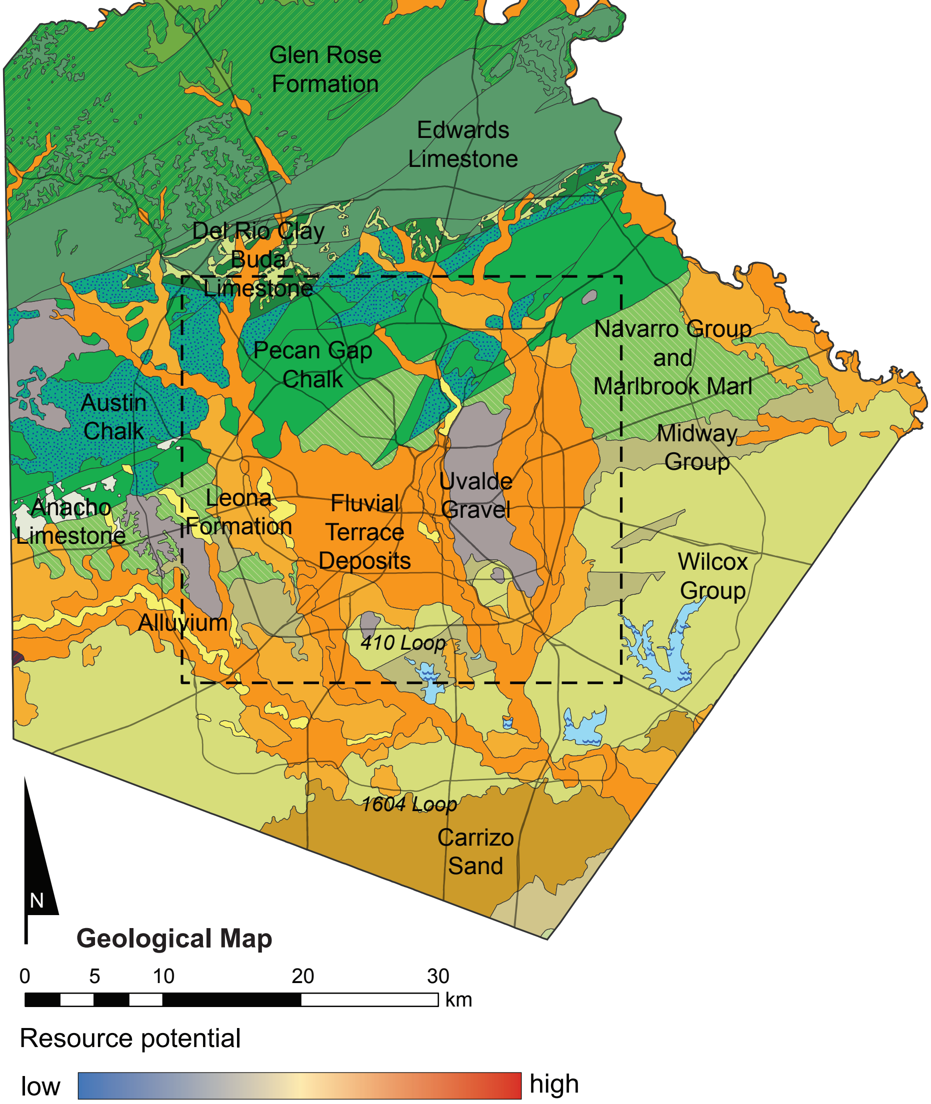
10 Ibid.

11 United States Geological Survey, "Mineral Resources On Line Spatial Data," Internet Map (USGS, 2014), http://mrdata.usgs.gov/general/map.html.

12 Texas State Historical Association, "Texas Almanac: Nonpetroleum Materials" (Texas State Historical Association, Internet), http://www.texasalmanac.com/topics/business/nonpetroleum-minerals.

13 Lisa Y. Taylor, "San Antonio's Quarries Help Keep Costs of Area Construction Projects in Line," *San Antonio Business Journal*, May 19, 2002, http://www.bizjournals.com/sanantonio/stories/2002/05/20/focus1.html.

Figure 3.1.2. Geological map of San Antonio (Bexar County)



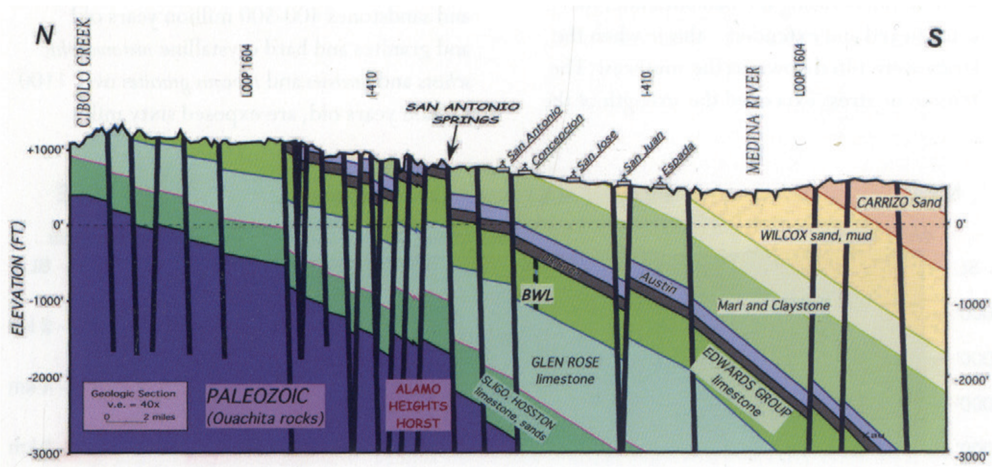


Figure 3.1.3. Geological section of San Antonio from north to south (Ewing, 2008, p.11)

within certain limits, in order to continue to provide drinking water to current and future populations. The flow of the aquifer varies from 0.4 to 4 m^2/s throughout the region,[14] making pollution difficult to control and its source difficult to identify. The Edwards Aquifer Protection Program has existed in several forms since the 1950s and regulates the types of activities and permits necessary in order to build or operate in the recharge, transition and contributing zones.[15] A section of the Texas Administrative Code directly addresses these three zones, requiring special permission to build roads, highways, residential buildings of a particular size, storage tanks and to clear or excavate. The recharge zone is perceived as the area most at risk and the contributing zone the least at risk.[16]

With the apparent abundance and low cost of petroleum and natural gas in Texas, there are only a few cases of harnessing the conductive capacity of the geology and temperature of underground water resources for heating, cooling or electricity production. A report published by the Texas State Energy Conservation Office named geothermal energy as an untapped potential, in particular for three affordances of geothermal energy: (1) geothermal heating, ventilation and air-conditioning systems (HVAC) systems through geoexchange (the conduction of heat into or out of the ground), (2) direct use (such as for spas) and (3) electrical power production (using vaporized water pressure to run turbines).[17] The subsurface temperatures in the San Antonio area favor all three of these uses, with electrical production more feasible (and cost-effective) in existing oil or gas fields (in the southern portion of the county) where extraction tends to remove large volumes of pressurized hot water at the same time. Geothermal HVAC systems are the applications that are most likely to appeal to private home and building owners, and the management of underground resources would need to consider their interactions with other uses. The authors of the report underline the need to manage the extraction and discharge loops of water, where geothermal systems are open (or are producing electricity using geopressured-geothermal resources).[18] Closed systems that rely on thermal conductivity (geoexchange) risk creating a short-circuit from an upper aquifer to a lower one, which could risk in pollution, as well as going so deep that they impede potential future activities in the underground.[19]

The San Antonio 2020 visioning process conducted through a series of public forums and over 5000 surveys from 2010 to 2011

[14] R. J. Lindgren et al., "Conceptualization and Simulation of the Edwards Aquifer, San Antonio Region, Texas: U.S. Geological Survey Scientific Investigations Report 2004-5277.," 2004.

[15] "Regulatory History of the Edwards Aquifer," accessed July 1, 2015, https://www.tceq.texas.gov/field/eapp/history.html.2015, https://www.tceq.texas.gov/field/eapp/history.html.

[16] Texas Secretary of State, *Environmental Quality: Edwards Aquifer*, *Texas Administrative Code*, vol. 30, 2016, sec. 213, https://texreg.sos.state.tx.us/public/readtac$ext.ViewTAC?tac_view=3&ti=30&pt=1.

[17] Frontier Associates, "Texas Renewable Energy Resource Assessment" (Texas State Energy Conservation Office, 2008).

[18] Ibid.

[19] Pascal Blunier, "Méthodologie de Gestion Durable Des Ressources Du Sous-Sol Urbain" (Doctoral Dissertation, EPFL, 2009), http://library.epfl.ch/theses/?nr=4404.

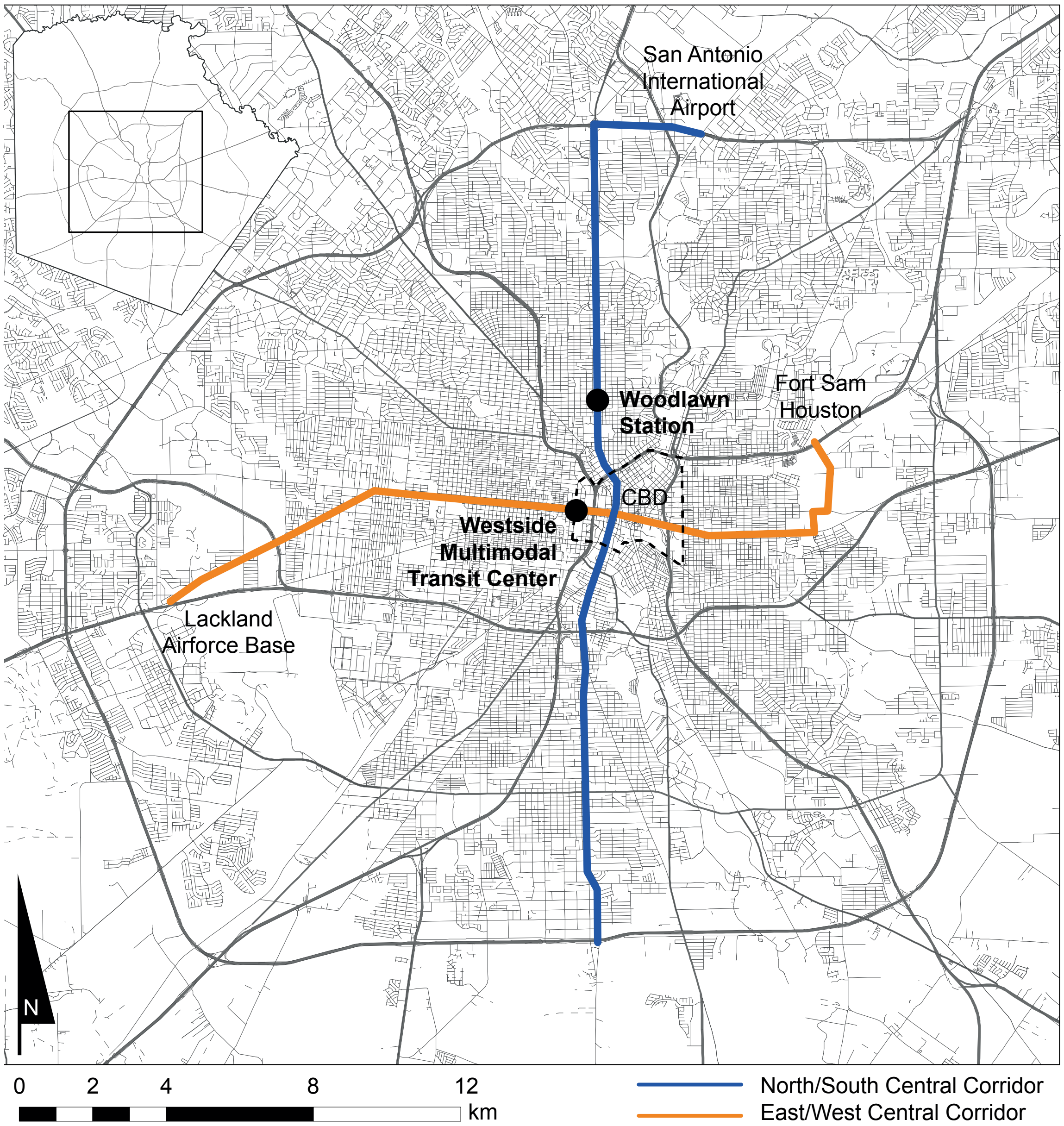


Figure 3.1.4. Forecasted surface rail or bus rapid transit corridors in the inner 410 loop (adapted from Jacobs Engineering, 2013)

laid out the urban planning objectives for the city for the next ten years. These objectives include increasing walkability and the number of pedestrian-oriented neighborhoods as well as concentrating development in existing urbanized areas.[20] The transportation plan for 2035 developed by VIA Metro Transit identifies seven main corridors for future public transportation projects, relying upon traffic and origin-destination data in addition to population and demographic forecasts.[21] These corridors seek to link the main activity hubs of the city, while decreasing congestion on existing arteries.

The North/South Central Corridor line runs from the San Antonio International Airport (Figure 3.1.4) near the northern segment of the inner 410 highway loop down through the

[20] Darryl Byrd, Sonia M. Rodriguez, and Graham Weston, "SA2020" (San Antonio, TX, 2011).

[21] Jacobs Engineering, "2035 Long Range Comprehensive Transportation Plan."

downtown (including the central business district) and south to an important mixed use development project. The transportation plan recommends light rail for this corridor given its importance in connecting “various southern and northern neighborhoods with major employers throughout the corridor, especially the core.”[22] The East/West Central corridor, recommended for bus rapid transit or light rail crosses the downtown, connecting Fort Sam Houston to the east and Lackland Air Force Base to the west (the US Department of Defense being an important employer in the region), passes through the downtown and connects the North/South Central Corridor to the Westside Multimodal Transit Center (WMTC), a future regional transit hub.

San Antonio’s relationship to its underground resources is currently dominated by the management of the aquifer system. Transportation objectives do not take into consideration any underground potential for the proposed lines or stations. Investigating the underground resource potential of the city will therefore serve to highlight other complementary underground potentials, examine as an example the two lines and stations proposed by the transportation plan and question the role underground resources could play in current and future planning practices, even if significant underground development is not a viable option in the short term.

3.1.2. Analysis: Data sources, transformation and conversion to relative scales

3.1.2.1. Data sources and transformations

In order to evaluate underground potential, several sources of data were compiled in a geographical information system (Table 3.1.1). The geological map published by the USGS was taken to represent the geological conditions at the near subsurface (excluding soils) and the substrata map published in a geological report from the 1960s was understood, when compared with sections available with the map

22 Ibid., 206.

Data	Source	Format	Initial Transformations
Superficial Geology	USGS	Polygon shapefile	None
Substrata (without alluvium)	Arnow (1963)	Raster TIF	Vectorized in ArcGIS
Local Well Data (n= 1529)	Texas Water Development Board	Point shapefile	Interpolation of groundwater saturation at 15 and 30 m depths.
Edwards Aquifer Zones	Edwards Aquifer Authority	Polygon shapefile	None
100-Year Flood Zones	Bexar County Open Data Portal	Polygon shapefile	None
Bexar County Parcels in 2010 (n=420,339)	Bexar County Appraisal District (BCAD)	Polygon shapefile	Conversion to address points using the street network as a geolocator
Bexar County Roads	BCAD	Line shapefile	None
Resident Population per Census Tract	U.S. 2010 Census Data	Polygon shapefile	Distribution of population counts by relative surface area to BCAD residential parcels located in the census tract.

Table 3.1.1. San Antonio resource potential data sources and initial transformations necessary.

and in other sources, to represent the geology at about 30 meters deep.[23] In order to identify the location of groundwater (either from the Edwards or other locally confined aquifers), well data containing the potentiometric level of the groundwater (the level to which it would rise in its artesian state) was converted from point data to a raster surface using a kriging algorithm available in ArcGIS 10.3. The regulated aquifer zones and the 100-year flood zones were also included as conditioning the affordance of the geology in particular areas. The urban form of the surface was represented using data from the Bexar County Appraisal District (BCAD), which records the current value, activities and built surface area of all land within the boundary of the county. A spatial network model was built in ArcGIS by locating the parcels as address points along street segments. The resident population of each parcel was estimated using U.S. Census data available in GIS format distributed proportionally to each BCAD residential parcel within the tract. Excluding the data acquired for a nominal fee by writing to the BCAD, all data is freely available online.

3.1.2.2. From geological formations to geotypes

In order to make it easier for non-specialists to return to the geological information if necessary during the planning process and to facilitate comparisons with other contexts, the formations were classified into geotypes (see Section 3.0.2.1). For example, four geological formations characterized by a predominance of chalk or marl and possible karstic voids, which increases the likelihood of a higher water content, but also affects their stability and thermal conductivity, correspond to the Alternating Marls and Limestones geotype (MC). This geotype is found in the northern part of the city and constitutes the areas where most of the urbanization has occurred. The main geological formations of San Antonio (fifteen occurred most frequently according to the atlas) correspond to seven

[23] Ted Arnow, "Ground-Water Geology of Bexar County, Texas," Geological Survey Water-Supply Paper (Washington, D.C.: US Government Printing Office, 1963); Ewing, *Landscapes, Water and Man*.

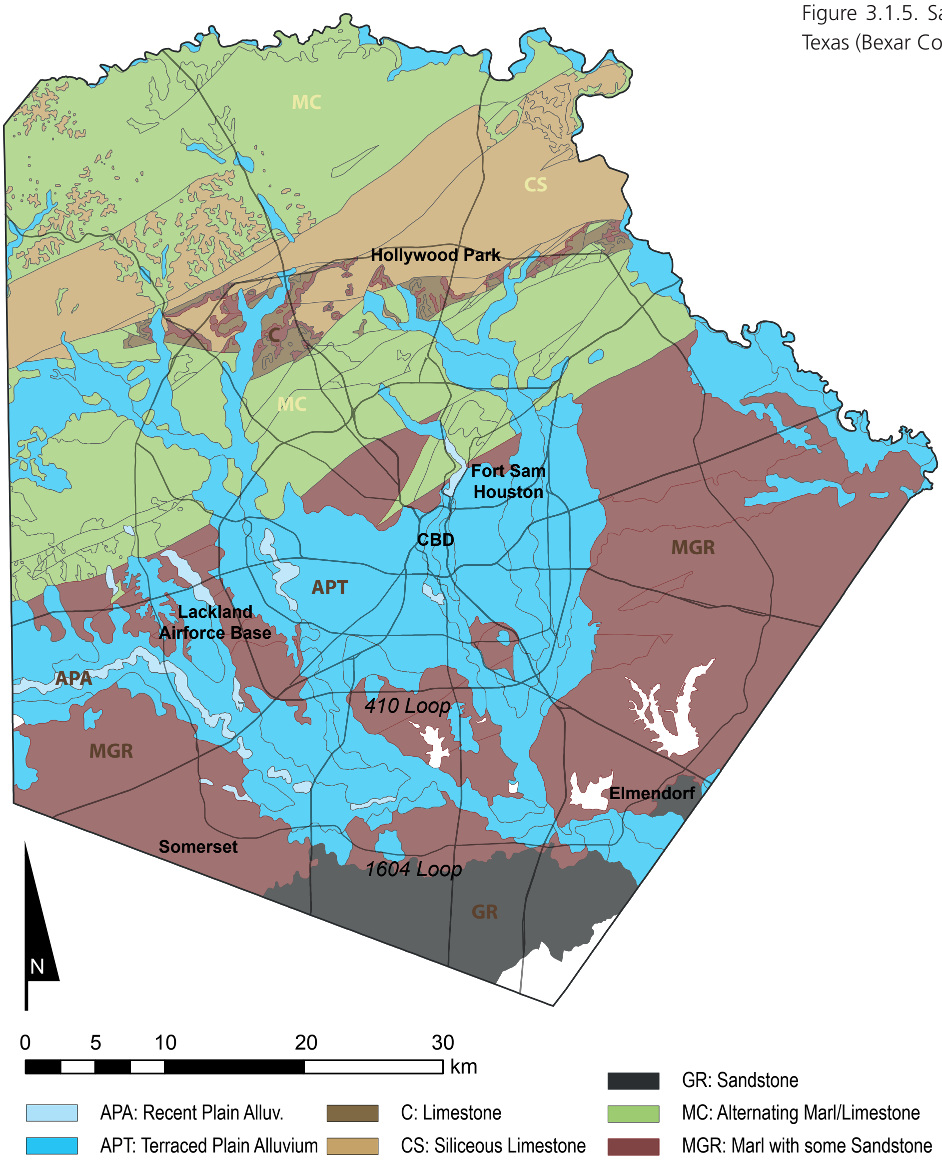


Figure 3.1.5. San Antonio Geotypes, Texas (Bexar County).

Code	Geotype Name	Formations in San Antonio (map label)
APA	Recent Plain Alluvium	Alluvium (Qal)
APT	Terrace Plain Alluvium	Fluviale Terrace Deposits (Qt) Leona Formation (Qle) Uvalde Gravel (T-Qu)
CS	Siliceous Limestone	Edwards Limestone (Ked)
MC	Alternating Marls and Limestones	Pecan Gap Chalk (Kpg) Anacacho Limestone (Kac) Austin Chalk (Kau) Glen Rose Formation (Kgru-C-Kgrl)
MGR	Marls with Some Sandstones	Wilcox Group (Ewi) Midway Group (Emi) Navarro Group and Marlbrook Marl (Kknm) Del Rio Clay (Kdr)
GR	Sandstone	Carrizo Sand (Ec)
C	Limestone	Buda Limestone (Kbu)

Table 3.1.2. Geotypes and corresponding geological formations for San Antonio (N.B. the acronyms correspond to the French nomenclature).

geotypes (Table 3.1.2, Figure 3.1.5): a series of younger superficial formations varying from six to fifteen meters deep (APA and APT) following the alluvial plains of the Medina and San Antonio rivers and the Salado and Leon creeks, two limestone types (C and CS) situated around the northern sector of 1604 near the municipalities of Hollywood Park and Shavano Park, a hard chalk and limestone (MC) type already mentioned and found on either side of the C and CS formations and two clay (MGR) and sand (GR) geo-types found mostly in the southern half of the city from Lackland and Fort Sam Houston military bases to the municipalities of Somerset and Elmendorf.[24]

3.1.2.3. Vectors of potential: evaluating the suitability of the geotypes for four resources

The next step evaluated the relative suitability of geotypes for construction of space, extraction of groundwater, heating and cooling from geothermal energy and use as geomaterials. Pairwise comparisons are carried out using scientific or expert (tacit) knowledge on a scale from one to nine.[25] For example, in calculating space suitability of the geotypes, each type is compared through pairwise comparisons to other types. The CS geotype was judged by the team (the author, a professor of geology and a professor of economics) to be more suitable for construction of space than the GR type due to the greater ease of construction in a limestone type than in sandstone. Due to possible holes in the karstic Edwards Limestone, the CS was considered to be slightly less suitable than the C type. These initial impressions were crossed with mineral resource locations[26] and exploitation[27] as well as geothermal data.[28] The relative importance of each geotype was further developed through discussions with geologists in San Antonio in the winter of 2014.[29]

Pairwise comparisons were performed for each of the geotypes according to the four resources on a scale from one to nine, as described in Section 3.0.2.2. For instance, the comparison matrix for suitability for space development (Table 3.1.3), after being normalized using the sum of the matrix, places the geotypes on a ratio scale in decreasing level of suitability: C (31%), MC (28%), CS (18%), APT (9%), MGR (6%), GR (5%) and APA (3%). The comparison of two geotypes looks at how much more suitable (in general) one is than another based on its compactness, granularity and consistency.[30] The consistency of the matrix can be determined

[24] Ewing, *Landscapes, Water and Man*.

[25] Thomas L. Saaty, "How to Make a Decision: The Analytic Hierarchy Process," *European Journal of Operational Research* 48, no. 1 (September 1990): 9–26.

[26] United States Geological Survey, "Mineral Resources On Line Spatial Data."

[27] Texas State Historical Association, "Texas Almanac: Nonpetroleum Materials."

[28] D.D. Blackwell and M. Richards, "Geothermal Map of North America" (American Assoc. Petroleum Geologist (AAPG), 2004), http://smu.edu/geothermal/2004namap/2004namap.htm.

[29] Ideally, the pairwise comparisons are carried out by the local specialists themselves, something that was not organized for San Antonio, but has been tested by the author in later case studies.

[30] This information was available for San Antonio in the notes accompanying the USGS geological map Bureau

Geotypes	APA	APT	CS	MC	MGR	GR	C	Suitability Vector (%)
APA	1.00	0.25	0.33	0.17	0.50	0.50	0.17	**3**
APT	4.00	1.00	0.33	0.20	2.00	2.00	0.17	**9**
CS	3.00	3.00	1.00	0.50	4.00	5.00	0.50	**18**
MC	6.00	5.00	2.00	1.00	4.00	5.00	1.00	**28**
MGR	2.00	0.50	0.25	0.25	1.00	2.00	0.17	**6**
GR	2.00	0.50	0.20	0.20	0.50	1.00	0.20	**5**
C	6.00	6.00	2.00	1.00	6.00	5.00	1.00	**31**

Table 3.1.3. Comparison matrix for the suitability of each geotype for space construction.

by taking the average of the eigenvalues of each geotype (basically a type's overall relationship to each of the other geotypes), subtracting from it the number of elements (here, five) and dividing it by one less the number of elements (four). This number is then compared to the average consistency of around 500 randomly-generated matrices of the same dimension to verify that the perturbations do not deviate more than 10 percent, which for the matrix here is 4 percent.[31] Consistency evaluates how well the rule of transitivity is respected in the pairwise comparisons—for instance, whether the relationship between geotypes C and GR is proportional to the relationships between C and APT and APT and GR.

3.1.2.4. Vectors of potentiality: the Edwards Aquifer Protection Areas

The Edwards aquifer, as one of the main if not the sole drinking water source for much of Central Texas, including San Antonio, has been under different forms of protection since the 1950s.[32] The Edwards Aquifer Protection Program regulates the types of activities and construction permits necessary in order to operate in three different zones. These zones include the recharge zone (where "stratigraphic units constituting the Edwards crop out", 30 TAC § 213.3(27)), the transition zone (where "faults, fractures and other geologic features present a possible avenue for recharge of surface water to the Edwards Aquifer" (30 TAC § 213.3(36))

	Outside	Contributing	Transition	Recharge	Suitability Vector (%)
Outside Protection Area	1.00	3.00	5.00	9.00	**55**
Contributing	0.33	1.00	3.00	7.00	**26**
Transition Zone	0.20	0.33	1.00	6.00	**14**
Recharge Zone	0.11	0.14	0.17	1.00	**5**

Table 3.1.4. Comparison matrix for the Edwards Protection Zones.

and the contributing zone (where "runoff from precipitations flows downgradient to the recharge zone" (30 TAC § 213.22(2)). The chapter of the Texas Administrative Code that specifically addresses

of Economic Geology, "Geologic Atlas of Texas, San Antonio Sheet" (Austin: Bureau of Economic Geology, 1983)..

31 Saaty, "How to Make a Decision."

32 "Regulatory History of the Edwards Aquifer." https://www.tceq.texas.gov/field/eapp/history.html"

the Edwards Aquifer (30 TAC 213) suggests that the recharge and transition zones are the highest risk areas (with the recharge zone riskier than the transition zone) with moderate risk to be taken into account in the contributing zone. This appreciation of risk was referred to in producing a comparison matrix and generating relative weights for the three zones plus the unregulated area (Table 3.1.4). The priority given to being outside the protection is much higher than being in any of the three zones with a decreasing priority from the contributing to transition to recharge zones.

3.1.2.5. Vectors of potentiality: Urban potential

Urban potential for San Antonio was calculated using accessibility to resident population and commercial floor area of Bexar county parcels acquired as shapefiles from the Bexar County Appraisal Office's 2013 dataset.[33] Resident population per census tract was proportionally distributed over the parcels identified as residential within the tract boundary. Because employment data was not available at the parcel or tract level, commercial value per square meter served as a proxy for the relative attractiveness of each commercial location. Commercial area for each parcel was available in the Appraisal Office's dataset as gross built floor area. The degree of centrality and accessibility on foot to resident population and commercial area, measured on the street network, was calculated for each parcel (n=420,339). In ESRI's ArcMap 10.3, each parcel was represented by a single point placed approximately along the street network according to its address.

The commercial centrality of each parcel is calculated as the sum of the distance to all commercial activities within 800 meters along the street network. As the travel mode of interest here is walking, the street network dataset built in ArcGIS excluded highways and highway ramps inaccessible to pedestrians. Furthermore, closer activities were given a higher weight using an exponential distance decay for pedestrian travel, which considers that nearly ninety percent of trips completed on foot are within ten minutes (or about 800 meters) from a point of departure.[34] The resulting value is referred to in this paper as *commercial destination potential*. Centrality to residential population, or *residential destination potential* was calculated in the same way. In addition to being centrally located, parcels may lie along the shortest paths between origins and destinations. This property, known as *betweenness*, evaluates the potential of a particular location to be passed in front of by trips occurring between locations at a given distance.[35] The resulting value, *commercial path potential,* is the sum of the number of trips that would pass by a parcel from all commercial origin and destination pairs at a given distance. Weighting the parcels according

[33] Acquired through a written request made directly to the BCAD office: http://www.bcad.org.

[34] S L Handy and D A Niemeier, "Measuring Accessibility: An Exploration of Issues and Alternatives," *Environment and Planning A* 29, no. 7 (1997): 1175–94.

[35] For one of many mathematical descriptions, see Porta et al., 2009.

to resident population approximates *residential path potential*, or the potential numbers of passers-by going from residential location to residential location.

Residential path and *destination potential* and *commercial path* and *destination potential* are the four metrics used to account for the potential of the current built environment to accommodate underground commercial spaces. Like geotypes, relative weights are established using pairwise comparisons where experience is difficult to quantify. The rare studies that have investigated retail location behavior allow us to hypothesize that being situated along shortest paths (betweenness) will be between 1.3 and 1.4 times as important as being nearby (gravity).[36] In the case of the relationship between the metric of proximity (gravity) and betweenness, the analysis of Montreal's Indoor City (Chapter 2), suggests that the relative importance of access to residents for the rental value of underground spaces may be dependent upon the existing distribution of housing units as well as zoning laws. A similar study conducted in Cambridge, Massachusetts, of surface food and retail stores argues that where housing is more evenly distributed, it may make less of a difference for stores to be near residential population (i.e. demand maximizing favors existing commercial areas over residential ones).[37] The resulting suitability vector takes into account this empirical evidence of proportion between the metrics (Table 3.1.6).

	Commercial	Residential	Metric	Priority vector (%)
Commercial potential	1.00	7.00	Path (1.3x)	**50**
			Destination	**38**
Residential potential	0.14	1.00	Path (1.3x)	**7**
			Destination	**5**

Table 3.1.6. Comparison matrix for urban potential measures

3.1.2.6. Creating aggregate potentials

The overall buildable underground space potential was estimated by combining the geology as an evaluation criterion with several others. Preference is given to locations where the groundwater saturation is lower, that are outside of 100-year flood zones and the Edwards protection zones and where parcel commercial and population centrality is higher. Each additional criterion was quantified according to its own internal relationships. For instance, it was considered to be preferable to be outside or inside the areas of lower

36 Sevtsuk's work in Cambridge, Massachusetts specifically looked at the influence of the betweenness, closeness (similar to gravity but without decay) of street segments on the probability that a location would be chosen by a food or retail owner Andres Sevtsuk, "Path and Place: A Study of Urban Geometry and Retail Activity in Cambridge and Somerville, MA" (Doctoral Dissertation, Massachusetts Institute of Technology, Dept of Urban Studies and Planning, 2010).. Porta and colleagues' research on Bologna, Italy, investigated the same metrics looking this time at retail densities Sergio Porta et al., "Street Centrality and Densities of Retail and Services in Bologna, Italy," *Environment and Planning B: Planning and Design* 36, no. 3 (2009): 450–65. The fact that their results are similar (1.3 and 1.4 respectively) is interesting. Of course, more research is needed to show that this is not simply coincidental.

37 Sevtsuk, "Path and Place: A Study of Urban Geometry and Retail Activity in Cambridge and Somerville, MA."

	Geotype Potential	Urban Centralities	100-Year Flood Zones	Aquifer Prot. Zones	% of GW at Depth	Suitability Vector (%)
Geotype potential	1.00	3.00	4.00	6.00	8.00	**49**
Urban centralities	0.33	1.00	2.00	3.00	4.00	**21**
100-year flood zones	0.25	0.50	1.00	5.00	5.00	**19**
Aquifer protection zones	0.17	0.33	0.20	1.00	3.00	**8**
% Groundwater at depth	0.13	0.25	0.20	0.33	1.00	**4**

Table 3.1.7. Comparison matrix for the potential of buildable underground space.

risk of the aquifer protection zones. Groundwater saturation was left as continuous values (where less is always better in the case of the space potential). This additional data constituted the elements in a new matrix constructed for each resource, the pairwise comparisons for which were carried out through discussions among the authors. For the potential of buildable underground space (Table 3.1.7) the quality of the geology was judged to be more important than the amount of groundwater present, because the presence of groundwater is an approximate estimation based on well data. Local investigations would have to follow once certain areas of interest were identified.

In evaluating the potential of the geological formations as geomaterials, the pairwise comparisons were based upon the general water content and granularity of each geotype. The pairwise comparisons also took into account the current use of the formations in the local market. For instance, the important role of limestone in local construction (geotypes CS and MC) placed it higher on the relative scale than sandstone (geotypes GR and MGR). Geomaterial extraction was also considered to be more favorable outside aquifer protection zones, where extraction practices are regulated and limited and where there is less groundwater present in the first 30 meters. The geological properties, presence of groundwater and the aquifer protection zones contributed proportionally to the overall geomaterial potential score by declaring the geological properties of 'very strong importance' (7 out of 9 on the scale adopted by the AHP) in relationship to the aquifer protection zones and of 'essential or strong importance' (5 out of 9) in relationship to the level of groundwater. The percentage of groundwater present was evaluated also of 'essential or strong importance' over the aquifer protection zones (Table 3.1.8).

Relative groundwater potential and geothermal potential relied on two sources of data—the geological properties of the geotypes and the percentage of groundwater present in the first 30 meters as estimated using well data from the Texas Water Development Board. For groundwater potential, the pairwise comparisons relied on general water content and the permeability of the formations as indicated by previously mentioned sources.[38] Geothermal potential relied on the thermal conductivity of the geological formations,

[38] Bureau of Economic Geology, "Geologic Atlas of Texas, San Antonio Sheet"; Ewing, *Landscapes, Water and Man*.

	Geotype Potential	% of GW at Depth	Aquifer Prot. Zones	Priority Vector (%)
Geotype potential	1.00	5.00	7.00	**55**
% groundwater per depth	0.20	1.00	5.00	**26**
Aquifer protection zones	0.14	0.20	1.00	**14**

Table 3.1.8. Comparison matrix for the overall geomaterial potential.

which resulted in higher rating, for instance, for the sandstone and marl formations (geotype MGR) than the quaternary formations (geotypes APA and APT) whose water content and density where found to be generally lower. The presence of groundwater in the first 30 meters made a positive contribution to the evaluation of both potentials. Due to the contribution that water saturation makes to thermal conductivity, the overall contribution to the geothermal potential of the presence of groundwater was judged to be higher. [39]

3.1.3. Synthesis: Mapping of Aggregate Criteria and Potentials

3.1.3.1. Individual resource potentials

The relative scales resulting from the calculation of potentials using pairwise comparisons are aggregated per resource (Figure 3.1.6). In the GIS model, this is accomplished by first converting all vector data into a raster dataset composed of 50x50 m cells and then calculating potentiality for each cell. Because the entire region for which data is available is of interest to us (here, at county level), conversion into a grid provides a single spatial unit that is divorced from political or topographical boundaries. The relative scores are situated between 0 and 1 (or 0 and 100 if presented as percentages) and can be compared from one resource to another. Zooming in to the central downtown area around the 410 loop (Figure 3.1.7), the potential for space in the first 15 meters is the most geographically varied, due to the scale of the spatial analysis situated at the parcel

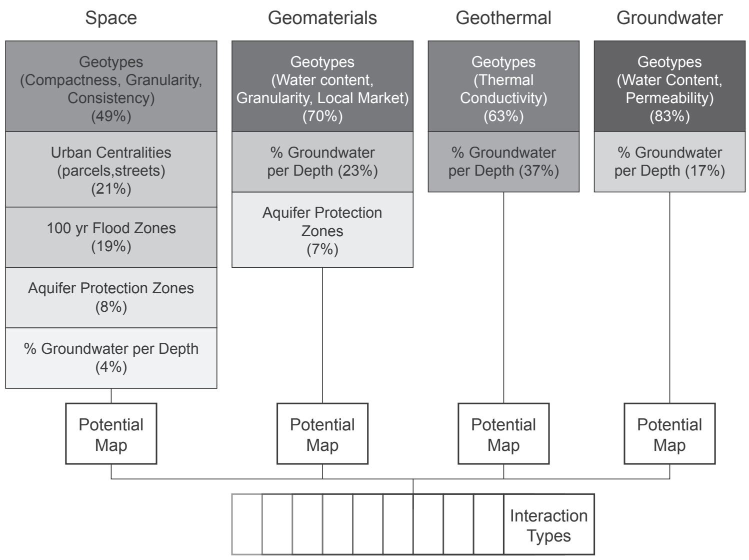


Figure 3.1.6. Aggregation procedure for the separate resource potentials and their interactions. Percentages represent the relative contribution of each criterion.

[39] Blunier, "Méthodologie de Gestion Durable Des Ressources Du Sous-Sol Urbain"; Aurèle Parriaux, *Géologie: bases pour l'ingénieur* (Lausanne, Suisse: Presses polytechniques et universitaires romandes, 2009).

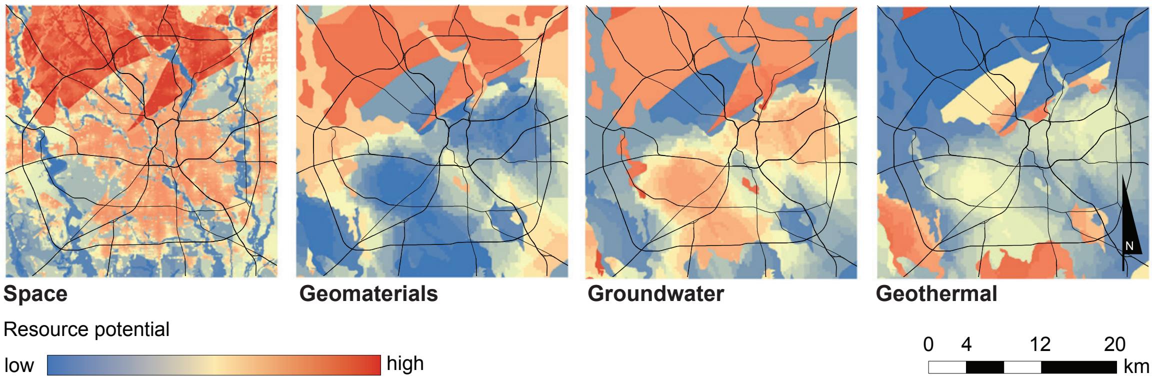


Figure 3.1.7. Individual resource potential maps for the urban area within the 410 loop (depth 0 to 15m).

level. The influence of the geology is evident in the areas of highest potential (red) which correspond to the approximate locations of the alternating marl and limestone geotype (MC). The presence of groundwater in the first 30 meters lowers the potential (blue areas) of the geology for geomaterial extraction, while raising the groundwater and geothermal potentials (visible as southwest and east sectors of the study area). Although three of the potentials overlap in the northern part of the study area, geothermal potential is highest mostly in the sandstone and clay geotype and in those areas that are saturated. In both situations, the thermal conductivity is relatively more favorable than in other locations.

3.1.3.2. Aggregating resource potentials

Separately, the four resource potential maps indicate the areas where there is a higher probability of finding a stable (compact and consistent), valuable and reusable geology, of varying water content and thermal conductivity. From these, potentials can begin to be derived: alternative sources of construction materials, of water for irrigation or drinking, and of energy extraction or electricity production. Although these maps already provide important information for different stakeholders to reevaluate and investigate in more detail their projections, this constitutes business as usual. As argued in Chapter 1, the move from a paradigm of 'needs to resources' to one of 'resources to needs' requires thinking multi-use—thinking in terms of creative combinations and mixtures of potentials.[40] This poses a particular challenge of performing aggregation in a meaningful way.

The classic solution, borrowing from AHP, is to combine the four maps according to a series of criteria weights. This is best illustrated by returning to the transit lines mentioned in the Section 3.1.1.1 (Figure 3.1.8). Although the envisioned transportation scenarios are entirely aboveground, it is interesting to examine the underground potentials of the two proposed stations. When combining the potential maps with an equal priority for each (consulting local decision-makers for this step was beyond the scope of the study),

[40] A. Parriaux, L. Tacher, and P. Joliquin, "The Hidden Side of Cities—towards Three-Dimensional Land Planning," *Energy and Buildings* 36, no. 4 (April 2004): 335–41.

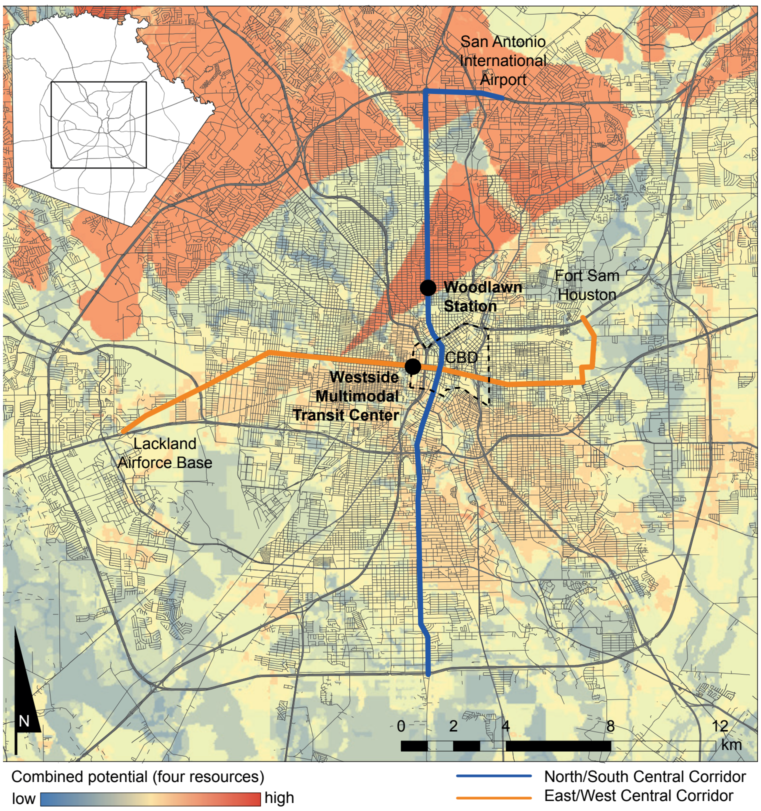


Figure 3.1.8. Aggregate resource potential at 0 to 15 meters deep overlaid by two future transit lines.

the Woodlawn station clearly has a relatively high combined potential (score of 81 out of 100), while the WMTC is situated in a zone of slightly higher than medium potential (combined score of 62). The separate scores for each resource potential (Figure 3.1.9) suggest that Woodlawn provides an opportunity for underground space construction, contains potentially interesting geomaterials (mostly limestone) and may support local groundwater extraction (for drinking or irrigation). Geothermal energy systems are not impossible, but may not be practical here, as the low score suggests. The WMTC does have some opportunity for underground space development, although it is situated over more clay-heavy ground, which reduces the potential for reuse of local geomaterials. Groundwater extraction (the site is situated over local aquifers according to well data) and geothermal energy systems may be of higher priority.

The centrality metrics reveal the potential of the sites to support underground commercial activities. The Woodlawn station is located at the intersection of two four-lane roads, San Pedro Avenue, which is north-south and mostly commercial, and Woodlawn avenue, a mostly residential east-west street comprised of two-story single-family homes. The parcels around the station score in the top 90th to 100th percentile for accessibility to commercial property values and residential population at a distance of about a 10-minute walk (800 meters) (Figure 3.1.10). Although with such low built density the construction of underground space is not yet a viable economic alternative to building on the surface, it remains a site of interest if

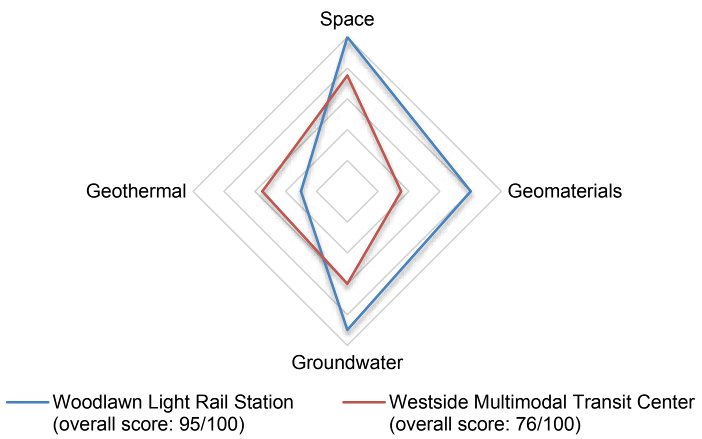


Figure 3.1.9. Comparison of resource potentials for two future transit stations.

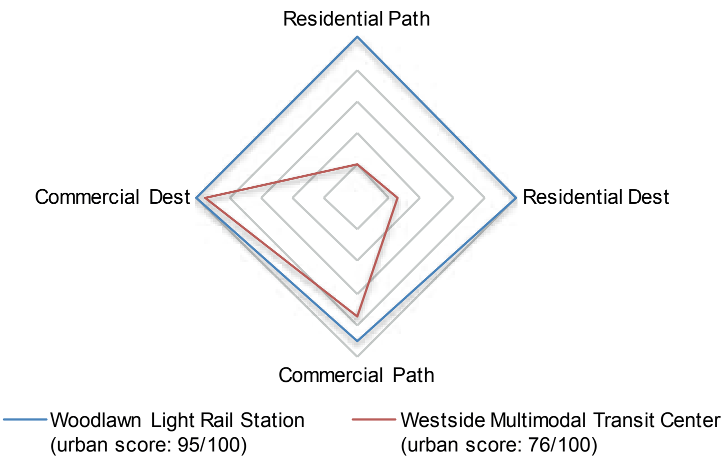


Figure 3.1.10. Comparison of urban centrality metrics for two future transit stations (San Antonio, TX).

the recommended transit line could be placed underground in the future.

In contrast to the Woodlawn station that is a local transit stop, the WMTC is a regional hub, located in an area just outside the western edge of the Central Business District next to a rail line. While it is not far from high-value commercial areas, it is less likely to be a chance stop for pedestrians on their way from one commercial location to another. From a standpoint of potential clientele, the WMTC would have to count on passengers being the main clientele to support underground commercial spaces and even then it may be more difficult to argue given its less favorable geological conditions.

Of course, the mapping method proposed here is meant to give a general overview and not to replace local investigations of soil properties, the built environment or economic conditions. The maps are intended to help inform a long term planning process that must deal with uncertainty, not only in the information upon which decisions are being made (data and its analyses), but also and most importantly in the number of criteria that must be satisfied in the evaluation of potential. The classic AHP calculation considers each criterion equally, meaning, for the mapping method proposed here, that aggregate potential is the sum of that of each resource. In order to capture the varying attitudes of decision-makers and

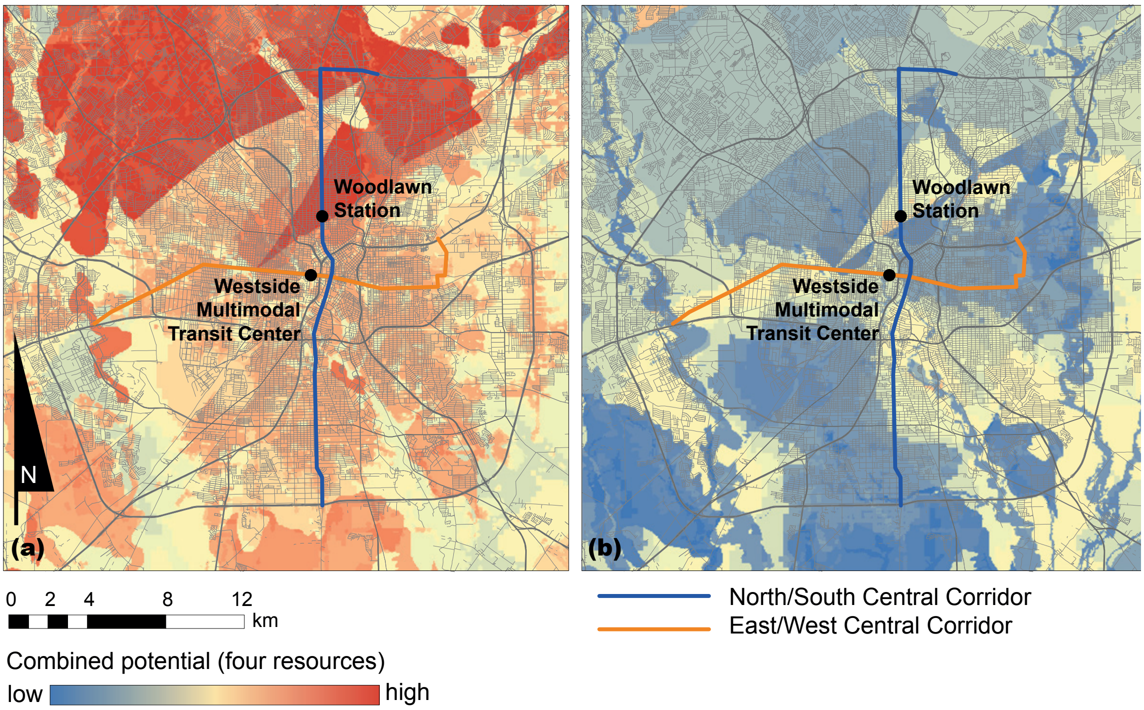


Figure 3.1.11. Aggregate maps with emphasis on the strongest (a) and weakest (b) resource potentials.

stakeholders towards the relative importance of the aggregated criteria, researchers have proposed incorporating order weights into the aggregation process.[41] Concretely, this means that for each location the mapping process reorders from highest to lowest the resource potential scores and multiplies them by an order vector that either places all the weight on the first (highest) or last (lowest) resource. This process, called Ordered Weighted Averaging (OWA), seeks to account for varying degrees of participation of criteria in the decision-making process. OWA allows the calculation of aggregate potential to present on a single map the locations where there are a few, but not all the same, high resource potentials. A second map can highlight locations where all four resources are similarly strong.

For instance, Woodlawn station and the WMTC's potential scores of 81 and 62, respectively, are the result of simply adding the four resource potentials together and normalizing their result (synonymous with a dummy order vector of [0.250, 0.250, 0.250, 0.250]).[42] If potential is calculated with only an appreciation for its highest potentials (using an order vector of [0.764, 0.182, 0.043, 0.010]), then Woodlawn's score moves to 98 and the WMTC's increases by 10 points to 72. Mapping these scores for the area around the 410 loop (Figure 3.1.11a) reveals those areas where there are one or several very high resource potentials. Areas of high geomaterial and geothermal potential emerge in the southern and western parts of the study area and the potential for space and groundwater is highest in the northern section. Using the reverse

41 Soheil Boroushaki and Jacek Malczewski, "Implementing an Extension of the Analytical Hierarchy Process Using Ordered Weighted Averaging Operators with Fuzzy Quantifiers in ArcGIS," *Computers & Geosciences* 34, no. 4 (April 2008): 399–410; Ronald R. Yager and Antoine Kelman, "An Extension of the Analytical Hierarchy Process Using OWA Operators," *Journal of Intelligent and Fuzzy Systems* 7 (1999): 401–17.

42 For a mathematical description and examples of using OWA, please see Yager & Kelman 1999.

order vector [0.010, 0.043, 0.182, 0.764], which emphasizes the weakest resource potentials, Woodlawn and the WMTC have nearly the same score (51 and 48 respectively), because their weakest potentials (geothermal and geomaterials) are nearly equal (as illustrated in Figure 3.1.8). The regional map of these scores highlights those areas where the resource potentials are collectively high (Figure 3.1.11b). The highest potentials (red zones) with this calculation are outside the 410 loop, over the aquifer recharge zone in the northern part of Bexar County.

For the planning process, the analysis produces a series of maps that tell a different, but complementary story, which can be revealed by stepping backwards through the aggregation process (a reversal of Figure 3.1.6). The three aggregation maps represent the mid-point and two extremes of a particular attitude toward the priority levels of the four underground resources without limiting the map to only one resource. Emphasizing the weakest resource potentials reveals the zones where potential conflicts and synergies are likely to be the most critical and where their interactions have to be planned more carefully. Emphasizing the strongest potentials reveals areas where one or two resource potentials are higher than the rest and where targeted efforts for the management of a particular resource could look first in priority.

3.1.3.3. Mapping potential interactions

Where the approach adopted in the previous section provides a way to visualize the four resource potentials in a single map, this section explores an alternative strategy that is indifferent to (admittedly volatile) attitudes towards risk. A multi-use approach places the emphasis on the potential to actualize multiple affordances in a single location. Previous research has laid out some examples of these, in both their positive (geothermal energy-collecting building foundations) and negative (aquifer-polluting geothermal conduits) forms.[43] Interactions between construction, excavation and the use of geothermal energy suggest different potentialities than those formed by interactions that include groundwater. They imply different discussions and different stakeholders who participate in those discussions. In order to produce interaction maps, we propose to characterize locations according to their degree of overlap in potential and to combine the extraction (geomaterials) and construction (space) potentialities because they are coupled in transformation activities. Three different potentialities means eight different combinations, including those where there is no presupposed interaction (e.g. where only geothermal scores highly). For example, an interaction between geothermal and groundwater potentialities is one in which the geothermal and groundwater

[43] Blunier, "Méthodologie de Gestion Durable Des Ressources Du Sous-Sol Urbain," 93; A. Parriaux et al., *Projet Deep city : ressources du sous-sol et développement durable des espaces urbains* (Lausanne: vdf Hochschulverlag AG an der ETH Zürich, 2010), 39.2010

both equal 1 (and where construction/excavation or space and geomaterials is 0).

A similarity index for each of the 1,301,102 locations in the 50 by 50-meter grid of Bexar County was calculated in ArgGIS using the eight resource potential combinations as candidate features. Normalizing their values (between 0 and 1) and plotting them according to percentiles reveals the dominant potentials in the county (Figure 3.1.12). Interactions between space, geomaterials, groundwater and geothermal (*SpGm+Gw+Gt* in Figure 3.1.12) as well as space and geomaterials and groundwater (*SpGm+Gw*) appear to be those that would need to be addressed over the largest part of the territory (with the 90th percentile situated between 0.9 and 1.0). The overall range of similarity scores suggest that interactions between all three potentialities (*SpGm+Gw+Gt*) is the most probable (with almost all values situated between 0.5 and 1.0). Interactions between space, geomaterials and groundwater, as well as geothermal

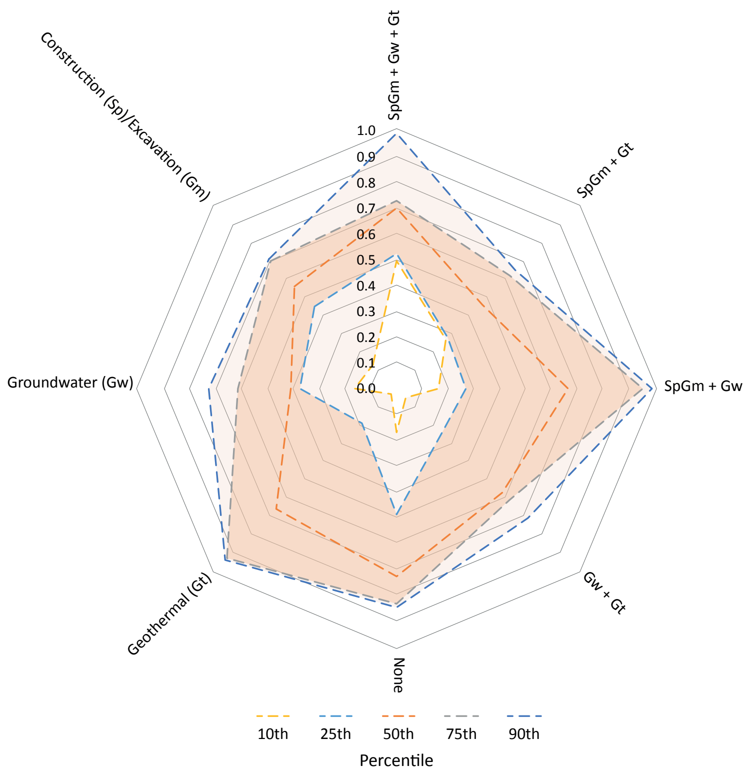


Figure 3.1.12. Distribution of degree of similarity to interaction types, presented as percentiles.

alone (with no interaction) have a larger range of middle values (that is, only half of all locations in the study area display a strong degree of similarity to these particular combinations).

3.1.4. Local potentiality: The underground potential of a future transit hub.

The significance of these values depends to a great deal on where they are located relative to current or forecasted settlement areas. For instance, interaction between the three resources has the highest potential in the central downtown area and in the northern half

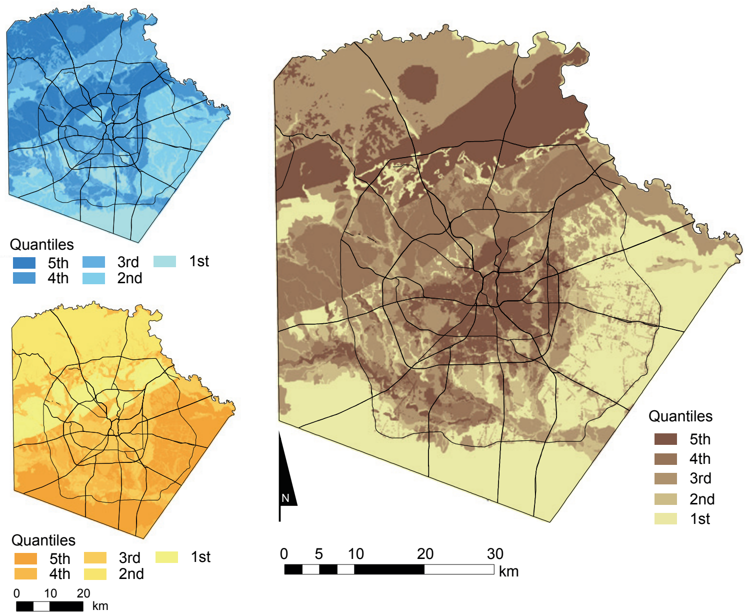


Figure 3.1.13. Maps of degree of similarity to two different types of interaction (top left: groundwater and space/geomaterials; right: space/geomaterials, groundwater and geothermal) and single-use geothermal (bottom left).

of Bexar County particularly over the limestone formations (CS, C) (Figure 3.1.13, right). Interactions between construction and excavation activities as well as groundwater extraction appears the most prevalent along the quaternary riverbeds and the mixed marl and limestone (MC) formations (Figure 3.1.13, top left). In the southern half of the county, in the clay and sand formations, are the areas where geothermal looks to be promising as a single use—there does not appear to be strong interactions with other resource potentials. This of course decreases slightly along areas that are locally central parcels, where the potential for space development is somewhat higher, the result of which is a slight lowering of the degree of similarity to the single-use geothermal category.

A more specific example helps to clarify further the interpretation of the interaction maps. One of the stations mentioned earlier, the Westside Multimodal Transit Center (WMTC), is a future transit hub from regional to local rail and is currently being developed aboveground. The evaluation using Order-Weighted Averaging and the classic AHP approach found that the WMTC would have a medium to low underground potential—although its highest potentials are for construction of underground space (because of its urban centrality), followed by geothermal and groundwater potential. Looking at the similarity scores for the eight combinations of resource potentials, the approximate appreciation our AHP and OWA provided is evident. The WMTC is situated in an area where it is most similar to a high combination of all three (its normalized similarity score is 0.82 for a maximum of 1.00) (Figure 3.1.14). This means that not only would any underground development on one resource have to engage with another, any intervention that does not incorporate the potential synergies between affordances is a lost opportunity.

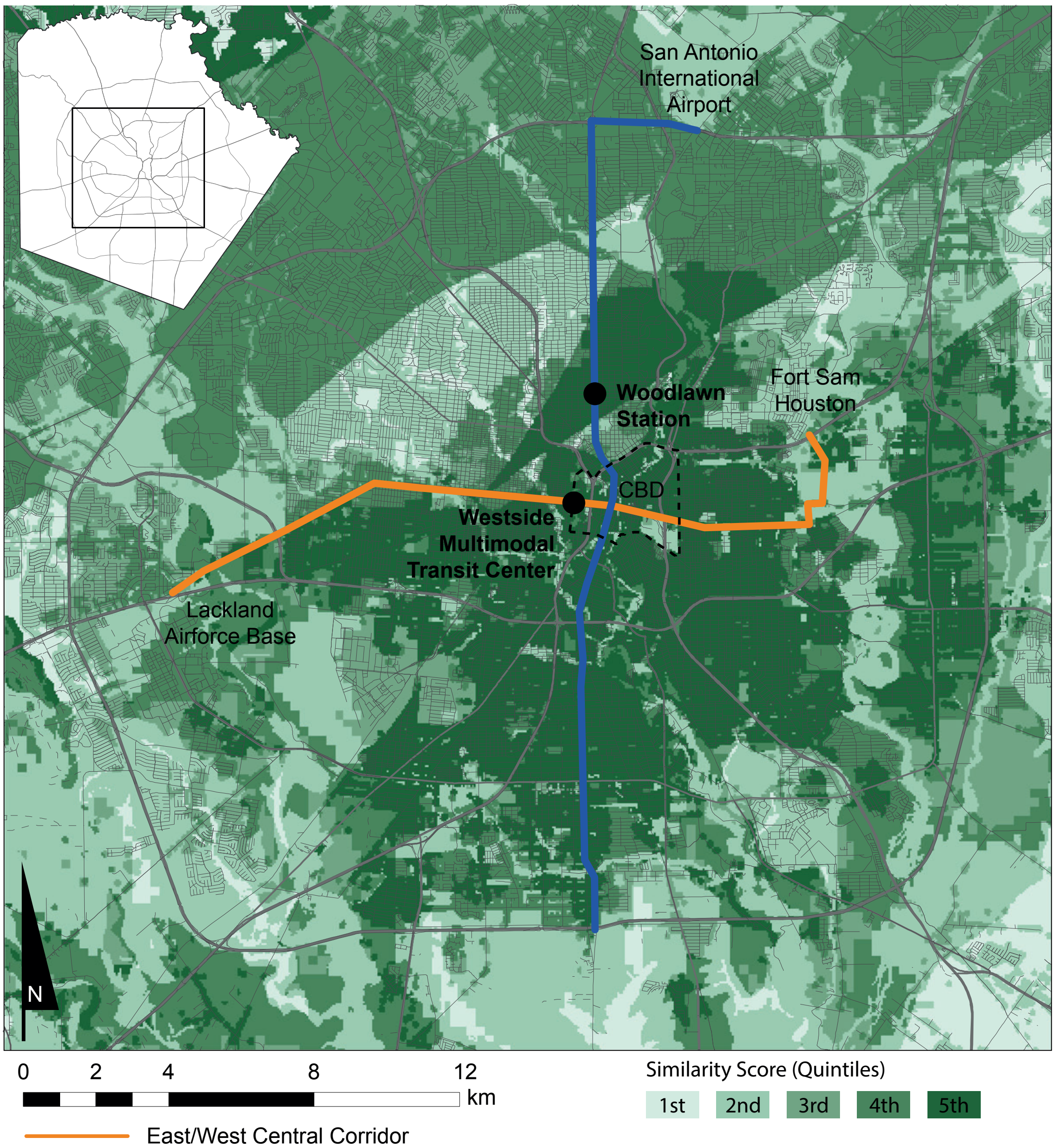


Figure 3.1.14. The Westside Multimodal Transition Center is characterized most strongly by a potentiality that encompasses excavation / construction, groundwater and geothermal energy.

3.1.5. Conclusion: The map as a compass

The mapping of resource potential in San Antonio is intended to inform the brainstorming or visioning process conducted by planners or urban designers prior to master planning. As such, they are most appropriate for the strategic phase. Like a compass, they can orient the planner without indicating a particular direction. They ensure that the urban volume is thought of in its multiple uses and affordances. The maps could provide criteria for multidisciplinary design charrettes or competitions where participants are asked to imagine multi-use scenarios that push the current limits of the urban volume. This is the contribution of maps that seek to establish the "conditions for the emergence of new realities"[44] and attests to the strength of cartography in the map overlay tradition.[45] The challenge is bridging the cartographical gap between urban planners and designers and the various disciplines whose expertise provides valuable information for the creative process. Following a visioning process, or multidisciplinary design competition, specific objectives can be formulated, missing data added or collected (where possible) or the existing data updated. Multicriteria decision-making can then begin to prescribe different directions for the design and planning process to take. For the public transit corridors in San Antonio, this would have meant strategically placing the surface lines so that they are already situated over areas of high underground potential. Even if the current financial means or political climate are not pursuing underground development, the conditions are set for future possibilities. This is also why resource potential needs to rely on as little (but relatively good) data as possible. Where investment has not occurred heavily in underground construction or resource management, data may be scarce and the motivation to collect it for a master planning process absent or of low priority.

Further work will fine-tune the methodology and test it in other contexts, which is presented in the next two chapters looking at Hong Kong and Dakar. One of the objectives is to test the pairwise comparison exercise with local experts. The legibility of the information contained in the interaction and resource potential maps would be improved by developing a series of sectional drawings and by reminding people working with them that multiple depths are of concern. Future work should also test the maps in a design or planning setting. Where this may not immediately occur in practice (and where the status quo often prevails), the academic environment could test the interaction maps within a design studio and present its proposals to local actors and stakeholders for feedback.

[44] James Corner, "The Agency of Mapping: Speculation, Critique and Invention," in *Mappings*, ed. Denis E. Cosgrove, Reprint, Critical Views (London: Reaktion Books, 2002), 214–300.

[45] Wybe Kuitert, "Urban Landscape Systems Understood by Geo-History Map Overlay," *Journal of Landscape Architecture* 8, no. 1 (May 2013): 54–63.

Chapter 3.2

Deep City Hong Kong

3.2.1. Conditions: Motors of an Economy of Avoidance and Encounter

When the British first arrived in Hong Kong in the mid-1800s, they founded their settlement on the northern coast of Hong Kong Island. The island's rugged and mountainous terrain provided protection for the colony, near present-day Central, from attack and from sea swells caused by typhoons in the South China Sea. Victoria, as the settlement was called at the time, was also strategically located for trade with the Chinese across the harbor, whose settlement was protected from northern invasion by the peaks of the Lion Rock Ridge. Trade and the influx of population (mostly from Mainland China) influenced the evolution of Hong Kong's landscape over the course of the next 175 years more radically than rain and wind had done for millennia. Chinese pine and the local granite became sources for building materials and influenced construction practices. The landscape was slowly transformed, creating additional buildable land off the coast by razing hills and repurposing excavated materials from the underground rail project and eventually underground spaces and gradually expanding the coastline into Victoria Harbor. Topographical space limitations and the spatial practices inherited from China have constantly recoded places and practices brought from Britain or imported from the urban planning or architectural bodies of theory in vogue.[1]

The first chapter presented the concept of an economy of avoidance and encounter, which operates through three—vectorial, transformational and informational—motors.[2] These motors rely on particular reservoirs or stocks in transporting, transforming or recoding mass. In Hong Kong, this mass is first of all material, in the extractions of materials for building and changing the landscape.

[1] Barrie Shelton, Justyna Karakiewicz, and Thomas Kvan, *The Making of Hong Kong: From Vertical to Volumetric*, 2014.

[2] Michel Serres, *La Distribution*, Hermès 4 (Paris: Editions de Minuit, 1977).

These vectorial motors have maintained a tradition inherited from the Chinese walled city forms of "rectilinear plans, dense building, multiple levels, mezzanine floors, tight external spaces and intense occupation."[3] Transportation infrastructures (road tunnels, trams, ferries, pedestrian under and overpasses, and the metro) have been transformational motors for the communications between relatively disconnected local centers. Road tunnels and the mostly underground MTR metro system have overcome topographical boundaries and densely trafficked thoroughfares.

Shelton and colleagues observe, however, that, despite a persistent government presence in building codes and zoning laws, these top-down normative structures have been frequently met with strong cultural recoding practices.[4] For example, the government responded to the housing shortage in the 1950s with the development of a series of H-shaped single-function residential blocks. Subverting the intended building program, the residents appropriated the building to their needs, often running business and light or cottage industries out of their flats and establishing community spaces on the rooftops. Rather than oppose and sanction these recoding practices, the government adapted subsequent types of the H-Block model to accommodate this mix of uses, planning for multiple levels of commercial activities with shops on the ground level and public facilities like schools and recreation areas on rooftops. These informational motors continue to condition each other and have in many ways enabled Hong Kong to evolve into the volumetric city it is today without an overarching planning ideology.

These motors have contributed to the unique, volumetric, urbanity of Hong Kong. The lack of dominant ideology has for the most part prevented overcoding the economy of encounter and avoidance in Hong Kong. Modernist urban planning principles were adapted to local conditions, maintaining high densities and overlapping functions, but without the kind of sprawl seen in the West. There nevertheless remains a risk of an informational motor evolving into a dominating agency. Shelton and colleagues, for example, remark a growing island mentality in the continuing development of dense and self-contained multifunctional towers—a tendency to over-concentrate activities on the interior and reduce permeability with the exterior creating enclaves much like gated communities, but without a control of access.[5] There is a parallel intensification of encounter with a corresponding increase in avoidance. In contrast, the economy of avoidance and encounter of the H-Blocks has been conditioned by the coding practices of both the authorities and the residents. To recall the terminology introduced in Chapter 1, this building type is more the result of overdetermination (conditioned

[3] Shelton, Karakiewicz, and Kvan, *The Making of Hong Kong*, 57.

[4] *The Making of Hong Kong*.

[5] Ibid.

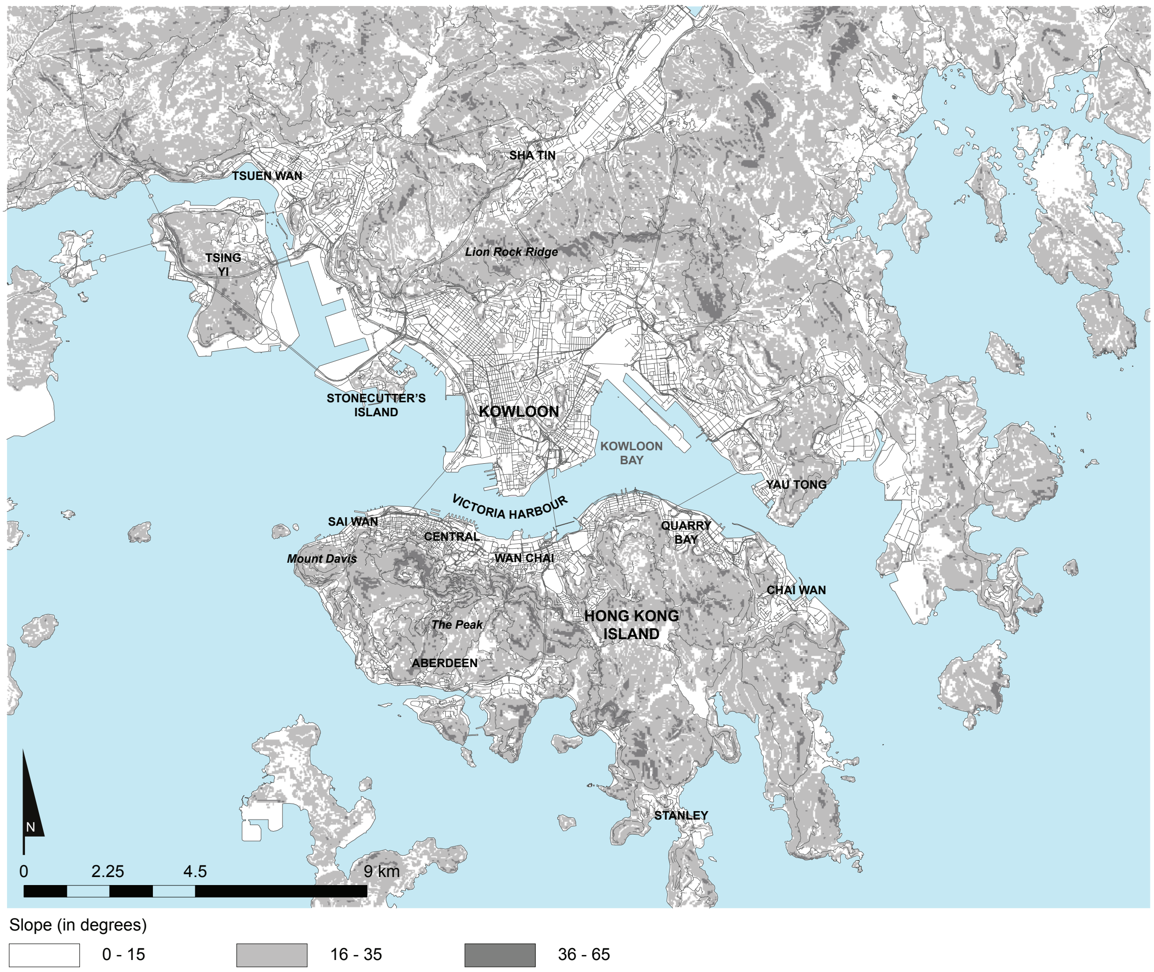


Figure 3.2.1. Inhabited areas, following the road network tend to be on flatter terrain with occasional routes going in to the mountains.

by a *variety* of causes or meanings), rather than overcoded by a dominant agency.[6]

Of the 1075 km^2 comprising the Special Administrative Region, 285 km^2 (27%) is inhabited by a population of 7.3 million (as of 2015) placing it among the densest human settlements in the world with an average population density of 22,600 people per square kilometer.[7] Perhaps paradoxically, Hong Kong continues today to face a shortage of land due to its rugged terrain. Expansion in Hong Kong remains limited by geography and topography, of which more than 60% of its surface area has a slope of 35° or more (Figure 3.2.1). Open spaces in a city of such density remain precious, and so topographical constraints are accompanied by a desire to preserve recreation areas and city parks.

Since the 1990s, a source of future transformation of the urban fabric and landscape has gained increasing importance. The mountains, which have bounded much of the urban expansion of Hong Kong Island and Kowloon, are now a potential source of future space for urban activities. They constitute a reservoir for extraction and removal, transformation into construction materials

6 See Chapter 1 or Levi R. Bryant, *Onto-Cartography: An Ontology of Machines and Media*, Speculative Realism (Edinburgh: Edinburgh University Press, 2014), Chapter 6.

7 Demographia, "Demographia World Urban Areas: 12th Annual Edition" (Belleville, Illinois: Demographia, 2016), www.demographia.com.

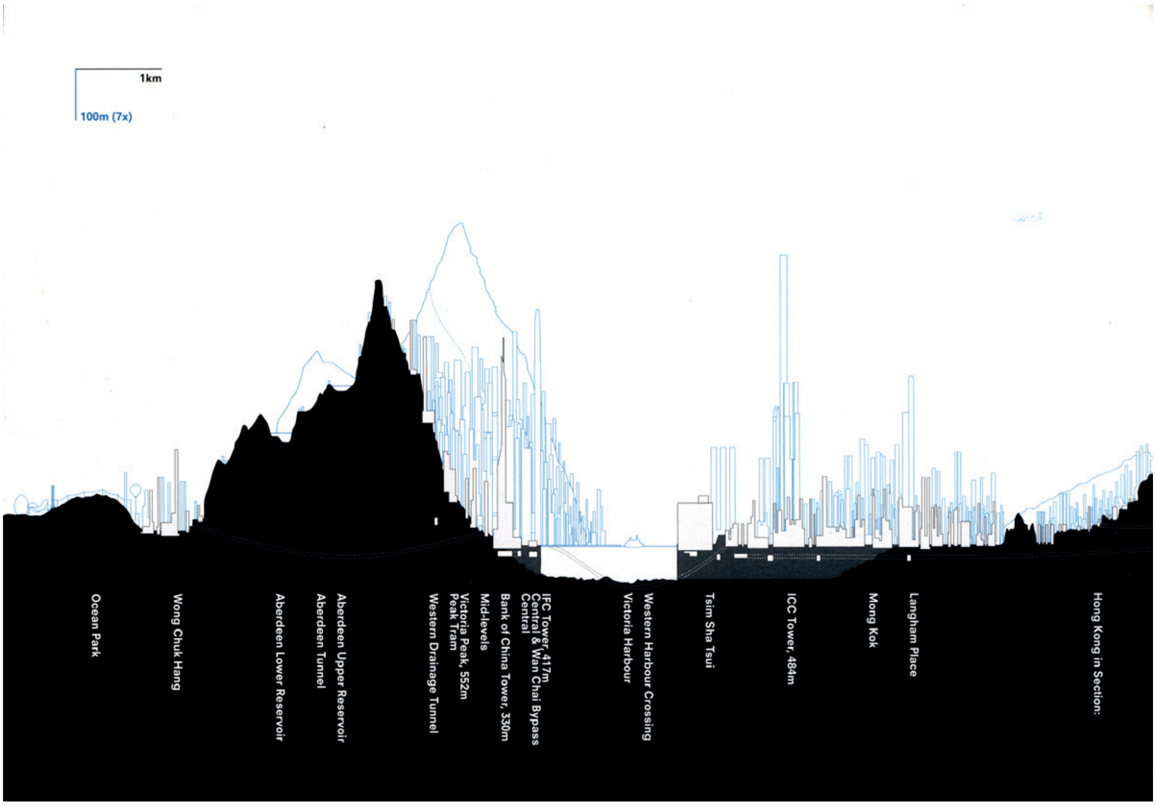
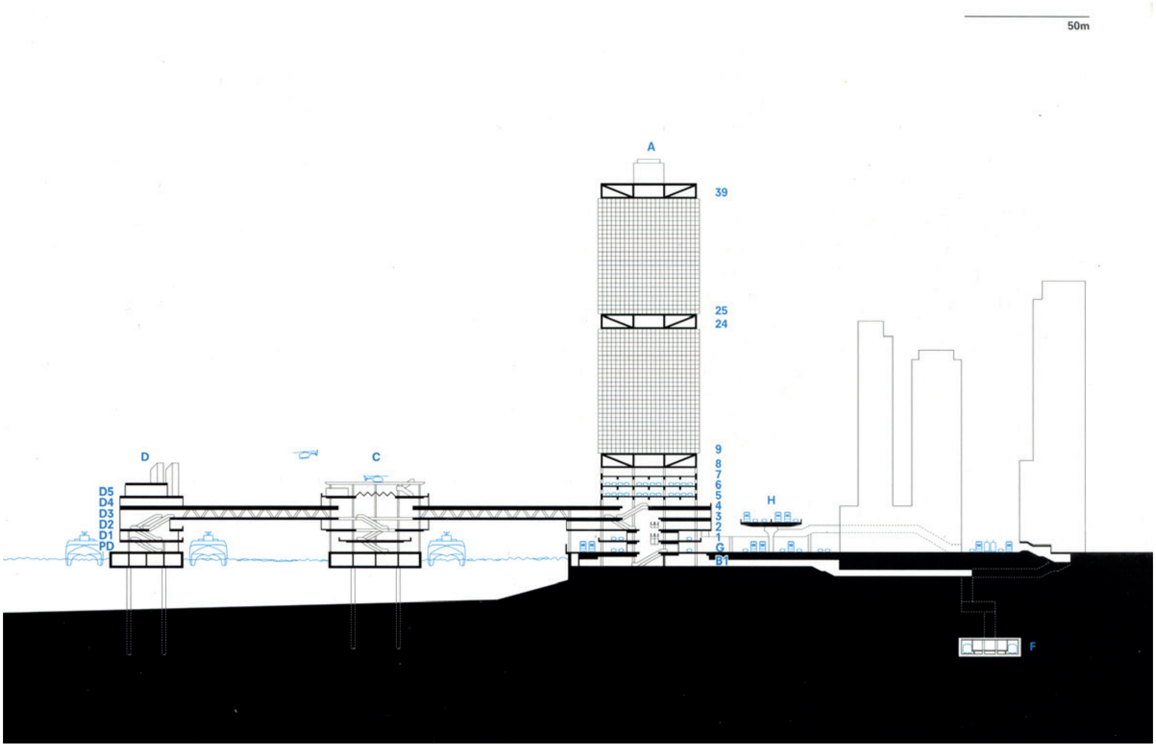


Figure 3.2.2. Urban section through Hong Island (left) through Victoria Harbor (middle) to Kowloon (right). Eight exaggeration of 7x the width (source: Frampton et al. 2012, p. 11). ▲

▼ Figure 3.2.3. Urban section through the Shun Tak Centre and docks in Sheung Wan, connecting at multiple levels the metro to the ferry lines (source: Frampton et al. 2012, p. 27).



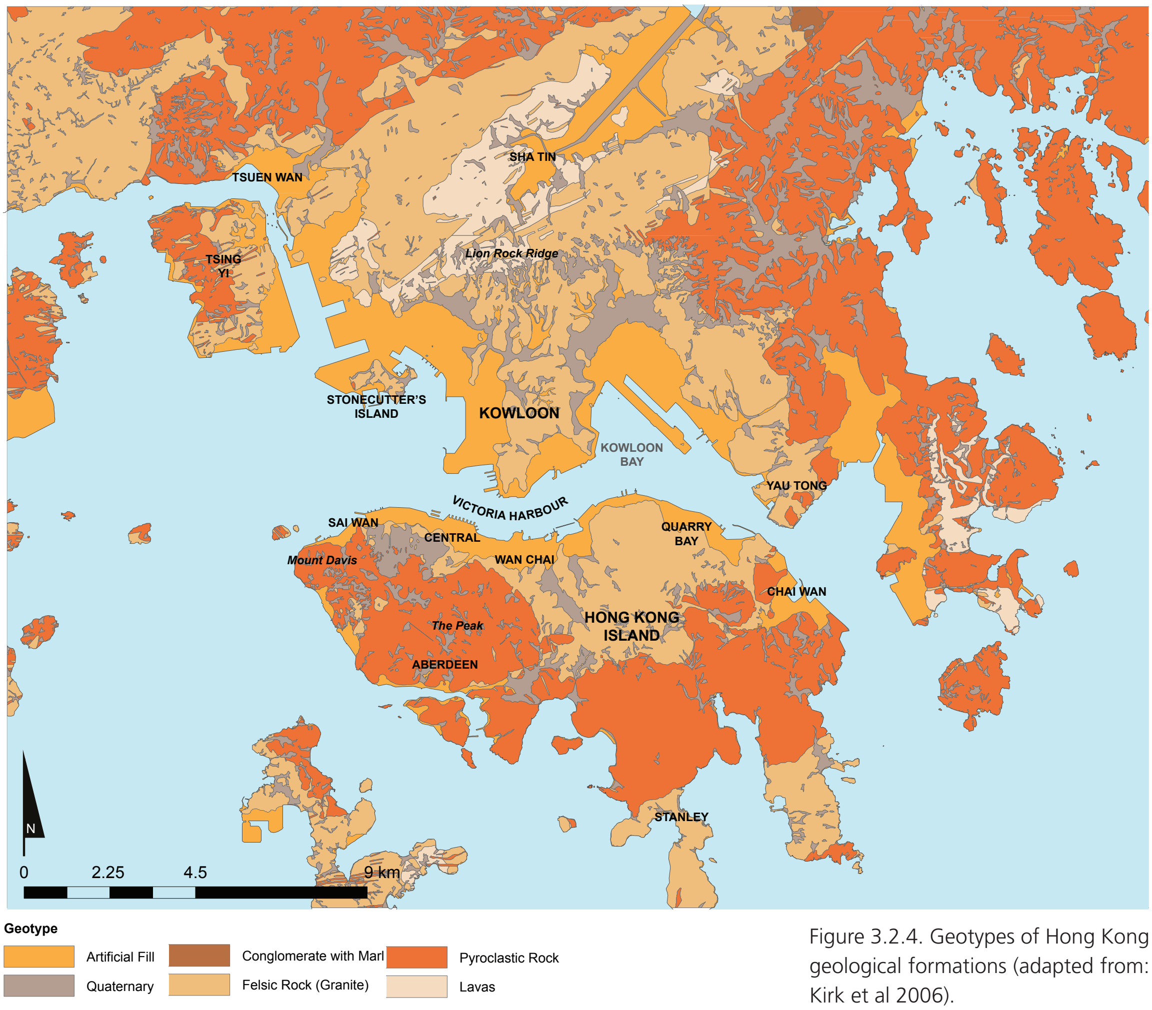


Figure 3.2.4. Geotypes of Hong Kong geological formations (adapted from: Kirk et al 2006).

and aggregate as well as an overall transformation of the city. They are the source of an informational motor of recoding and rezoning surface industrial uses to residential and commercial, moving certain government activities into caverns or beneath existing urban areas to free up surface land. Central to this informational motor is the evaluation and cartography of the potential of these caverns. How can this underground potential be presented in order to avoid overcoding future forms and preserve the rich variety of determining factors that have characterized the city? This chapter will explore this question by looking at the cavern suitability evaluation that is currently underway in Hong Kong and by conducting a complementary evaluation using the Deep City method.

3.2.2. Source to Resource: Cavern and Basement Potentials

3.2.1.1. Geotypes and Potentials for Space, Groundwater, Geothermal and Geomaterials

The geology underlying the developed areas on Hong Kong Island and Kowloon is mainly granite and volcanic rock (Figure 3.2.2). The most common types of granite are the Kowloon and Mount

Code	Geotype Name	Formations in Hong Kong	
R	Artificial Fill		
AP-AC-E	Quaternary Alluvium	Alluvium/colluvium	
FEL	Felsic Rock (Granite)	Mount Butler Granite (Klb) Po Toi Granite (Klp) Kowloon Granite (Klk) Tei Tong Tsui Quartz Monzonite (Klt) Tong Fuk Quartz Monzonite (Klf) Shui Chuen O Granite	Needle Hill Granite (Jkn) Tai Lam Granite (Jma) Tsing Shan Granite (Jms) Lantau Granite (Jml) Tai Po Grandodiorite (Jmt)
PYR	Pyroclastic Rock	High Island (Kkh) Clear Water Bay (Kkw) Mount Davis (Krd) Long Harbor (Krl) Che Kwu Shan (Krc)	Ap Lei Chau (Kra) Undifferentiated (Jlu) Tai Mo Shan (Jtm) Shing Mun (Jts) Yim Tin Tsai (Jty)
LAV	Lavas	Pan Long Wan (Krp) Sha Tin Granite (Jkt)	East Lantau Rhyolite (Jkd) East Lantau Rhyodacite (Jkd)

Talbe 3.2.1. Geotypes of Hong Kong geological formations.

Butler Granites, with the former found on either side of Victoria Harbor and the latter found to south of the Lion Rock Ridge and in the lower elevation areas around Mount Butler. These granites formed at different times in history and are relatively uniform, but their manner of breaking down means that foundations may have to go through several layers of granite boulders to reach bedrock. In some areas, these igneous formations are below sea level and are covered by excavated material on reclamation areas.[8] However, in areas where weathering has decomposed the granite and where quaternary deposits (like sand and gravel) are abundant, intense rains can lead to landslides—a problem that has plagued Hong Kong over the course of its history.[9]

3.2.1.2. A history of underground space development

The MTR lines and adjacent underground spaces are early evidence of Hong Kong's search for additional space beneath existing buildings and streets. If this development sought to harness the geological potential in improving connectivity between existing areas and the future new towns, the city began to look to the mountains for additional space in the late 1980s.[10] The urban planning strategy published in 1988, 'Metroplan the Aims', mentions the potential of man-made rock caverns and was followed by as a series of feasibility studies looking at technical and economic viability. These studies focused particularly on the opportunities to relocate certain undesirable or unsightly activities (waste or storage facilities) underground. Commissioned by the government, under the direction of the Geotechnical and Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) of

8 Bernie Owen and Raynor Shaw, *Hong Kong Landscapes: Shaping the Barren Rock* (Hong Kong: Hong Kong Univ. Press, 2007).

9 Raymond S. Chan, *When hillsides collapse : a century of landslides in Hong Kong.*, 2nd Edition (Hong Kong: Civil Engineering and Development Department of Hong Kong, 2013).

10 Shelton, Karakiewicz, and Kvan, *The Making of Hong Kong*.

the Hong Kong SAR, the attention given to caverns has been mostly oriented towards public services and infrastructures.[11]

The attention given to the potential of cavern development in the 1990s generated a body of knowledge on the technical, financial and safety aspects of cavern construction, but led to little development. Only an explosives depot (Kau Shat Wan on Stonecutter's Island), a waste transfer facility beneath Mount Davis near Kennedy Town (western Hong Kong Island) and the Stanley Sewage Treatment Works (southern Hong Kong Island) are notable examples from this period.[12] In the early 2010s, cavern and underground space development began to make its way into the regional policy addresses (given annually by the chief executive of Hong Kong), where it is discussed under strategies for land supply. The address of 2011-2012 claimed the government would "actively explore the use of rock caverns to reprovision [repurpose] existing public facilities and release such sites for housing and other uses."[13] This active exploration was mandated to the British engineering firm Arup and Associates. The following year, the address added to the cavern feasibility study the "possibility of linking up the underground spaces of existing or planned structures in the urban areas."[14] By the following year, four strategic locations had been identified for a pilot study in the densest parts of the city (Kowloon and northern Hong Kong Island). The policy address of 2015 provided only a reminder of this pilot study. In 2016, the address announced the nearing completion of the Cavern Master Plan and the plan to "consult the public on the formulation of preliminary underground master plans" for the four pilot study areas.[15] The policy addresses do not only mention the underground as a source of additional space. Priority has continued to be placed on transforming, for residential use, disaffected industrial and agricultural parcels that have been reserved for no longer needed purposes and barren portions of the green belt.

Evaluation of cavern development potential has been carried out mostly by Arup and Associates under a mandate from the GEO and the CEDD. In the late 1990s, the GEO carried out internally a cavern area study of Kowloon, which proposed a classification strategy for potential based upon geology (formations and faults), existing or proposed subsurface infrastructure and topography.[16] The study proposed three levels of classification: I, II, and III, with I and

[11] M.I. Wallace and K.C. Ng, "Development and Application of Underground Space Use in Hong Kong," *Tunnelling and Underground Space Technology* 55 (May 2016): 257–79.

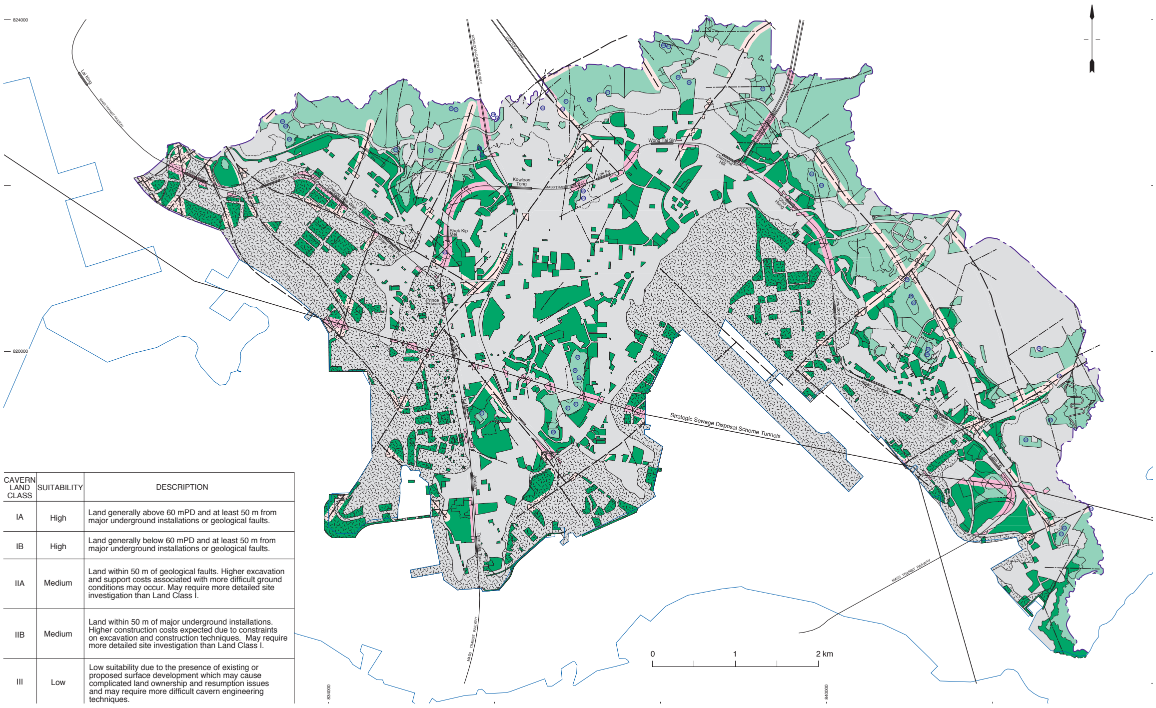
[12] Ibid.

[13] "The 2011-12 Policy Address of Hong Kong: From Strength to Strength" (Hong Kong, 2012), 12, http://www.policyaddress.gov.hk/11-12/eng/.

[14] "The 2013 Policy Address of Hong Kong: Seek Change, Maintain Stability, Serve the People with Pragmatism" (Hong Kong, 2013), 30, http://www.policyaddress.gov.hk/2013/eng/.

[15] "The 2016 Policy Address of Hong Kong: Innovate for the Economy, Improve Livelihood, Foster Harmony, Share Prosperity" (Hong Kong, 2016), 30, http://www.policyaddress.gov.hk/2016/eng/ As of August 2016, however, nothing had been released publicly on these public consultations.

[16] K. J. Roberts and P. A. Kirk, "Cavern Area Study of Kowloon," GEO Report (Hong Kong: Geotechnical Engineering Office, Civil Engineering Department, The Government of the Hong Kong Special Administrative Region, 2000).



CAVERN LAND CLASS	SUITABILITY	DESCRIPTION
IA	High	Land generally above 60 mPD and at least 50 m from major underground installations or geological faults.
IB	High	Land generally below 60 mPD and at least 50 m from major underground installations or geological faults.
IIA	Medium	Land within 50 m of geological faults. Higher excavation and support costs associated with more difficult ground conditions may occur. May require more detailed site investigation than Land Class I.
IIB	Medium	Land within 50 m of major underground installations. Higher construction costs expected due to constraints on excavation and construction techniques. May require more detailed site investigation than Land Class I.
III	Low	Low suitability due to the presence of existing or proposed surface development which may cause complicated land ownership and resumption issues and may require more difficult cavern engineering techniques.

Figure 3.2.5. Kowloon Cavern Area Study. Green areas are of high potential (source: Roberts & Kirk, plate 1).

II having sub categories A and B. Potential was reported by zone and parcel (Figure 3.2.5). In its cavern feasibility study, Arup adopted the criteria from Roberts and Kirk[17] and added several additional criteria: existing or planned land uses for public land, boreholes and areas with suspected or confirmed poor geology (sedimentary units in metamorphic rocks), reclamation and fill areas, scheduled areas (for specific infrastructural projects), landfill areas (where gas and pollutant containment would prove onerous) and impounding reservoirs (surface retention areas). The four cavern suitability classes prioritize locations that are mostly open spaces and that do not encroach upon existing infrastructure (within 50 m) (Figures 3.2.6 and 3.2.7, Table 3.2.2). Their study, which covered all of the Hong Kong SAR, found that 64% of the land in Hong Kong was suitable for cavern development.[18]

The cavern area study of Kowloon (Figure 3.2.5) shows a very localized scatter of cavern potential beneath existing parcels, most of which had not been developed on the surface at the time. The geological conditions of the reclamation areas are not considered problematic, although preference is given to places situated above sea level (here, to the northern border of the study area). This is one of the important factors taken into consideration in Arup's cavern master plan (Figures 3.2.6-7), but reclamation areas are rated low to very low. The part of the city constructed on the shoreline bordering Victoria Harbor is not a favorable location for cavern development. Scheduled areas and landfills also serve as limiting factors in cavern development potential, with the Mid-Levels (Hong Kong Island,

[17] Wallace and Ng, "Development and Application of Underground Space Use in Hong Kong."

[18] Mark Wallace, K. J. Roberts, and V Lau, "A Geographic Information Systems Approach for Regional Cavern Suitability Mapping for Hong Kong," in *Underground Space: Planning, Administration and Design Challenges* (14th World Conference of ACUUS, Seoul, 2014).

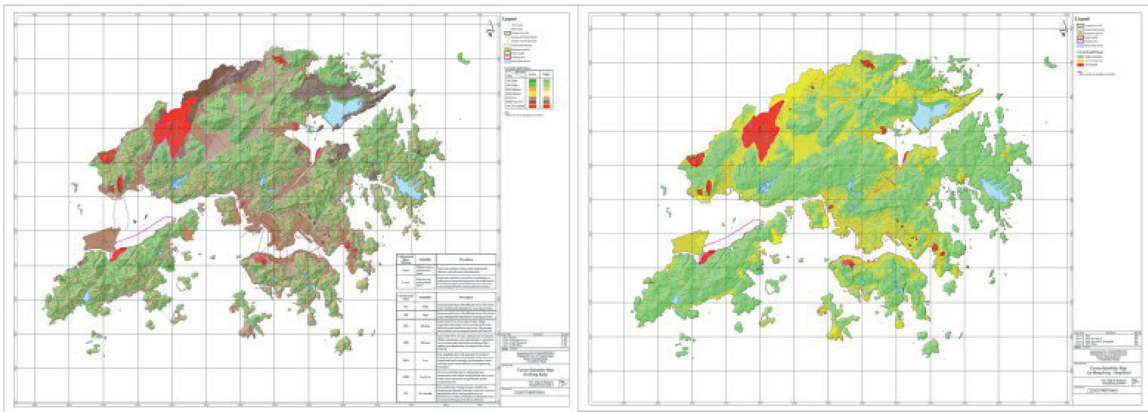


Figure 3.2.6. Cavern Master Plan, detailed and simplified versions (source: Wallace & Ng, 2016)

	Critical Values for Suitability Classes (from highest, SIA, to lowest, SIIIB)					
Criteria	SIA	SIB	SIIA	SIIB	SIIIA	SIIIB
Topography Zones	>60 mPD	<60 mPD	N/A	N/A	N/A	N/A
Landfill & Reclamation Area	No	"	No	"	Yes	"
Scheduled Area	No	"	No	"	Yes	"
Existing Cavern Sites	>60 m	"	>60 m	<60 m	N/A	N/A
Existing & Planned Tunnels	>60 m	"	>60 m	<60 m	N/A	N/A
Outline Zoning Plan Uses	Open/ public	"	Open/ public	"	N/A	N/A
Faults & Photolineaments	>50 m	"	<50 m	"	N/A	N/A
Boreholes	>50 m	"	<50 m	"	N/A	N/A
Sedimentary and Metamorphic Rocks	No	"	No	"	No	Yes

Table 3.2.2. The criteria and critical values for the Cavern Master Plan (adapted from Wallace et al. 2014).

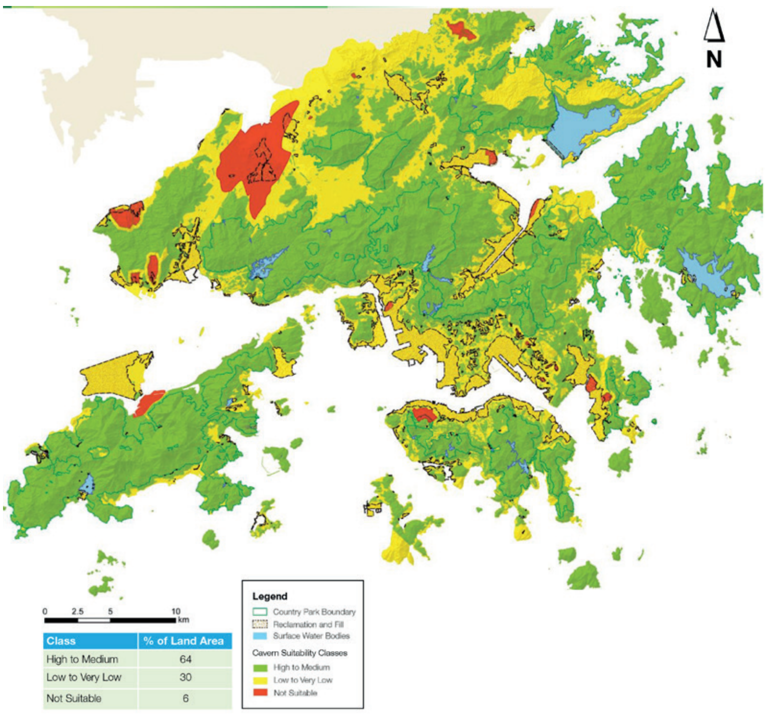


Figure 3.2.7. Simplified version of the Hong Kong Cavern Master Plan (source: CEDD & ARUP, 2009).

northwest area) excluded from cavern development and further east of Kowloon, at the Green Valley Landfill. Neither map differentiates according to the properties of the urban fabric. Even if the study of Kowloon indicates suitability at the parcel level, it does not suggest the potential of the urban fabric itself. The cavern master plan says even less. There are no locations on reclamation areas that might be interesting for cavern development in either the detail or simplified versions of the map. It would not be possible to know, for example, whether the interest in going underground at a particular location may be of higher priority than achieving the optimal geological conditions to do so. These are often economic decisions that are linked to the urban form.

Most of the cavern development in Hong Kong has been oriented towards government facilities that tend to be a nuisance for adjacent surface activities or an eyesore on the landscape. In this context, private sector engagement has been scarce and the CEDD made it explicit in their 2012 Study on Long-Term Strategy for Cavern Development that it was necessary to think of strategies to better engage with non-governmental actors.[19] Arup consulted a series of local actors working in various sectors, including warehouse and logistics facilities, data centers, wine storage, large-scale vehicle parking or storage and research laboratories and entertainment or cultural activities.[20] If the government is seeking to locate facilities away from settled areas, among the activities considered by Arup, only two would actually have a competitive advantage to being close to developed areas and easily accessible from them: retail and entertainment or cultural centers. Arup specifically looked at the limiting factors that affect shopping arcades and indoor sports arenas, claiming that suitable cavern areas would have to be near to MTR stations and to areas of easy access for delivery vehicles. Ross and colleagues cite the advantages of being in a naturally cooled space, although underline the important evacuation measures that would have to be considered for any cavern development frequented by a large number of people.[21]

The cavern master plan is fundamentally oriented towards the creation of underground space and the opportunity to use geomaterials for aggregate, without a complementary evaluation of groundwater or geothermal. This is not due to a conscious choice on the part of Arup, but rather the objectives of the mandate they received from the GEO. Indeed, the policy addresses underline the fact that cavern development is viewed as a solution to a land shortage problem. Alternate groundwater or energy sources are not a pressing need and so are not considered. This is an unfortunate oversight, but the plan in its current form leaves a lot open to interpretation.

19 Wallace and Ng, "Development and Application of Underground Space Use in Hong Kong."

20 Stuart Ross et al., "Recent Studies into the Feasibility of Developing Rock Cavern Facilities in a Dense Urban City," in *Underground Space: Planning, Administration and Design Challenges* (14th World Conference of ACUUS, Seoul, 2014).

21 Ibid.

Although lack of specific use is seen as problematic, it is actually an opportunity for creative adaptation. As a reservoir of potential, the map can be a source for multiple informational motors. It is in this light that the complementary basement potential maps are developed to augment the underground potentiality of Hong Kong.

3.2.3. Criteria and Data Sources

Deep City Hong Kong includes a series of criteria chosen through discussions with the Arup team.[22] Several criteria were adopted from the cavern master plan and others added (Table 3.2.3). Existing infrastructure was located by combining tunnels and existing underground spaces and placing a buffer of 60 meters around them. Flooding could have an impact on the potential of a location to be suitable to underground construction. Although there was no official flood zone map, the Drainage Services Department maintains a map of locations where flooding incidents have occurred. These incidents were communicated at the level of the street block unit. Street block units (SBU) are the smallest planning units (generally about 200 m^2) used in Hong Kong. In order to account for the quality of excavated materials, a layer of geology suitable for aggregate was provided by Arup. These three layers are presented in Figure 3.2.8.

Within the geological formations sitting over the bedrock, large boulders are located sporadically and can be up to several meters in diameter. These boulders, called corestones, are the result of weathering of the bedrock and the breaking down of the underlying weathering front (basically the top of the bedrock). Corestones are problematic for excavation because they are more difficult to remove than the surrounding alluvium and colluvium. In a study conducted in the late 90s of Kowloon, corestones were found to cluster in certain areas and were seemingly evenly scattered over the area according to borehole data.[23] A later study reported several in the area of Hong Kong Island around central, although they sometimes occur much deeper than 30 meters. In order to account for this particularity of the geology, two layers were produced using digitized borehole data—one locating the amount of 'soft' (disaggregate) geology in the first 30 meters; the other identifying locations in which corestones were thought to occur. Two continuous raster surfaces were produced by interpolating the data using a kriging algorithm available in ArcGIS, using the three nearest boreholes (Figure 3.2.9). In addition to geotechnical properties, topography was also considered important for underground ('basement') construction. Whereas altitude was taken as important for cavern construction (due to height limitations of cavern crown development), slope was considered to contribute

[22] In preparation for work in Hong Kong with the Arup and Associates team, an initial exercise translated the geological formations into geotypes and conducted a preliminary evaluation of their potential. The use of geotypes was later dropped, because geotypes are intended more for planners than geologists or geotechnical engineers who are more comfortable using their own descriptions of geological formations. The collaboration's focus on underground space, meant that geothermal energy and groundwater were not considered because of a lack of need for alternative sources of water and energy.

[23] R. Shaw, "Variations in Sub-Tropical Deep Weathering Profiles over the Kowloon Granite, Hong Kong," *Journal of the Geological Society* 154, no. 6 (December 1, 1997): 1077–85.

Criteria	Data Source(s)	Format	Initial Transformations
Existing UG Infrastructure	Arup (combination of caverns and tunnels)	Polyline and polygon SHP	Calculate buffer of 60 m
Zones of past major floods	Drainage Services Dept1. Arup (street block units)	JPEG Polygon SHP	Create polygon shapefile indicating street block unit (SBU) of flood incident
Geology suitable for aggregate	Arup (HK geological map)	Polygon SHP	None
Linear % of soft ground in first 30 meters	Arup (borehole data) (n = 14,469 boreholes)	Point SHP	Calculated the linear depth of soil above bedrock and interpolated a raster file to cover the whole HK SAR.
Linear % of corestones (weathered rock) in first 30 meters*	Arup (borehole data) (n = 954)	Point SHP	Calculated the linear depth of class III (weathered rock / corestones) and interpolated a raster file.
Topography (slope)	Arup (DEM)	Raster	None
Proximity to MTR	Arup (station outline)	Polygon SHP	Calculated proximity to station envelope at a 500m radius
Population destination and path potential (of street segment)	2011 Census2 (population per SBU) SMO3: street centerlines	Excel Polygon SHP Polyline SHP	Transfer of population density at street block level to street centerlines running through the SBU. Centrality analyses run on centerlines at 800 m radius.
Employment destination and path potential (of street segment)	2011 Census (population per TPU) SMO: street centerlines Arup (TPU)	Excel Polygon SHP Polygon SHP	Transfer of employment density at territorial block unit (TPU) to street centerlines. Centrality analyses run on street segments at 800 m radius.

N.B. SHP = ESRI shapefile or equivalent; *regardless of the characteristics of the rest of the ground.

Table 3.2.3. Criteria for Deep City Hong Kong, including data sources and transformations.

more to a location's potential for underground construction. A flat surface (slope of zero) is better for construction than the maximum slope of 65° found in Hong Kong. Slope information was extracted from Arup's digital elevation model.

As argued in Chapter 1 and incorporated in Deep City San Antonio, the existing urban form is a source of potential. In terms of the underground development of space, centrality metrics provide a general appreciation of how locations are related to each other. These spatial configurational relationships contribute in different ways to different activities. In testing this in Hong Kong, the analysis integrated centrality metrics of accessibility to resident population density and to the density of number of places of employment from street segments.[24] Addressing the existing concentrations of people and jobs relationally accounts for, for instance, low-density streets that are adjacent or on shortest paths to higher density areas, thus capturing a locational advantage.[25] Population and employment data were obtained from the 2011 Census. Population was reported by SBU and employment by (the larger) TPU (territorial planning unit), converted to density (based on planning unit surface area) and then applied to street segments. Accessibility metrics (betweenness and gravity) were calculated using the UNA Toolbox on the street segments, weighted according to this population or employment density. A radius of 800 meters was preferred to accommodate approximately 10 minutes walks. These analyses resulted in four

[24] For comparison, Deep City San Antonio used accessibility of parcels to commercial and residential surface areas.

[25] Lars Marcus, "Spatial Capital: A Proposal for an Extension of Space Syntax into a More General Urban Morphology," *Journal of Space Syntax* 1, no. 1 (2010): 30–40.

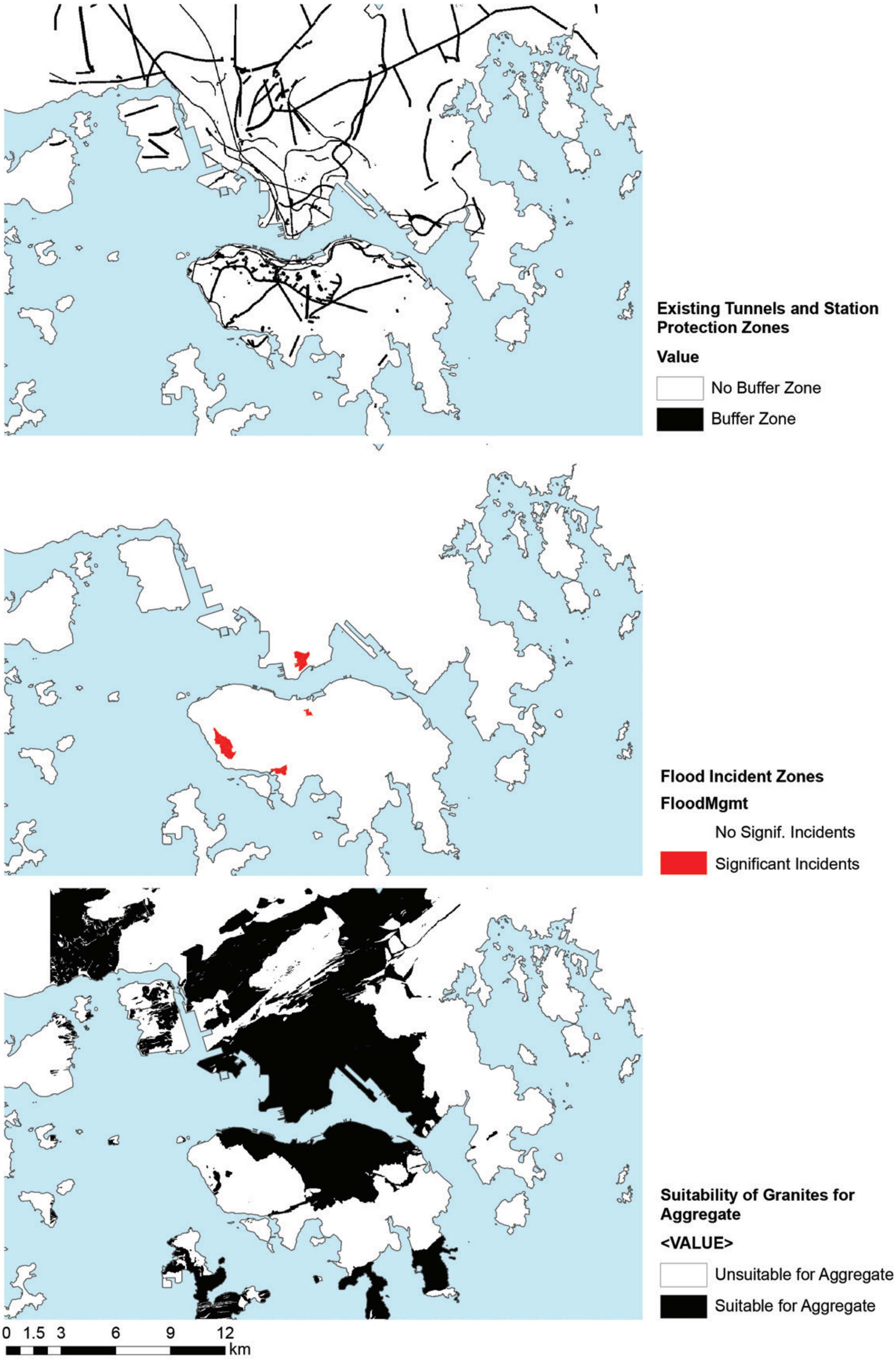


Figure 3.2.8. Evaluation criteria: existing infrastructure (top), zones of major flood incidents (middle) and suitability of granite for aggregate (bottom).

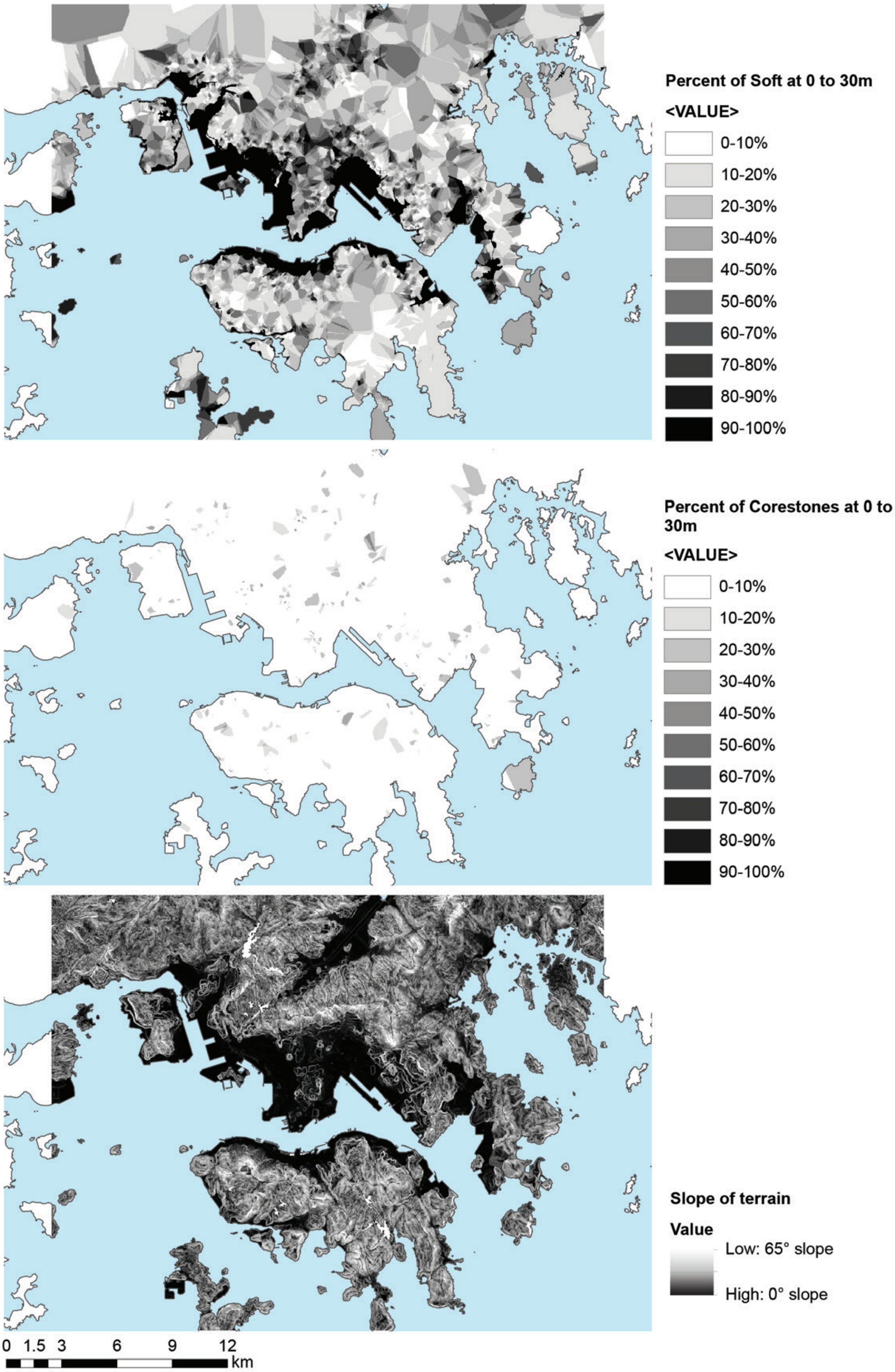


Figure 3.2.9. Evaluation criteria: Percent of soft ground (top) and corestones (middle) at 30 m, slope for basement potential (bottom).

raster layers capturing accessibility to population and to employment (Figures 3.2.10 and 3.2.11).

The spatial network model built for the centrality analyses incorporated both the road network, the MTR metro and the ferries. To account for the faster speed achieved by taking a ferry, ferry segments connecting wharfs were 'shortened' by calculating an average speed based on time of arrival and departure and establishing a proportion between the presumed pedestrian speed (with 800 meters in 10 minutes or 1.3 m/s) and the average ferry speed (16 km/h dock to dock). Discussions with Arup raised the question of capturing the general advantage of a location's being within a certain distance of the MTR station. In order to accommodate this advantage, access to the nearest (surface or subsurface) metro station (using the edges of the envelope, as not all street-level entry points were available) was calculated as a 'service area' using ArcGIS Network Analyst. A 500-meter radius was adopted in accordance with a study conducted by the MTR, which found that most MTR riders come from locations within 500 meters of a station.26

All criteria were converted to 25 m by 25 m raster grids and then compiled in a single polygon raster file where each layer was a column in the database file. The total grid size is 603,803 cells. Compiling into a single grid facilitated calculations performed later on multiple layers in the table, in particular the aggregation procedures using relative priority weights and fuzzy qualifiers presented in the next section.

[26] Bo-Sin Tang et al., "Study of the Integrated Rail-Property Development Model" (Hong Kong: The Hong Kong Polytechnic University, 2004).

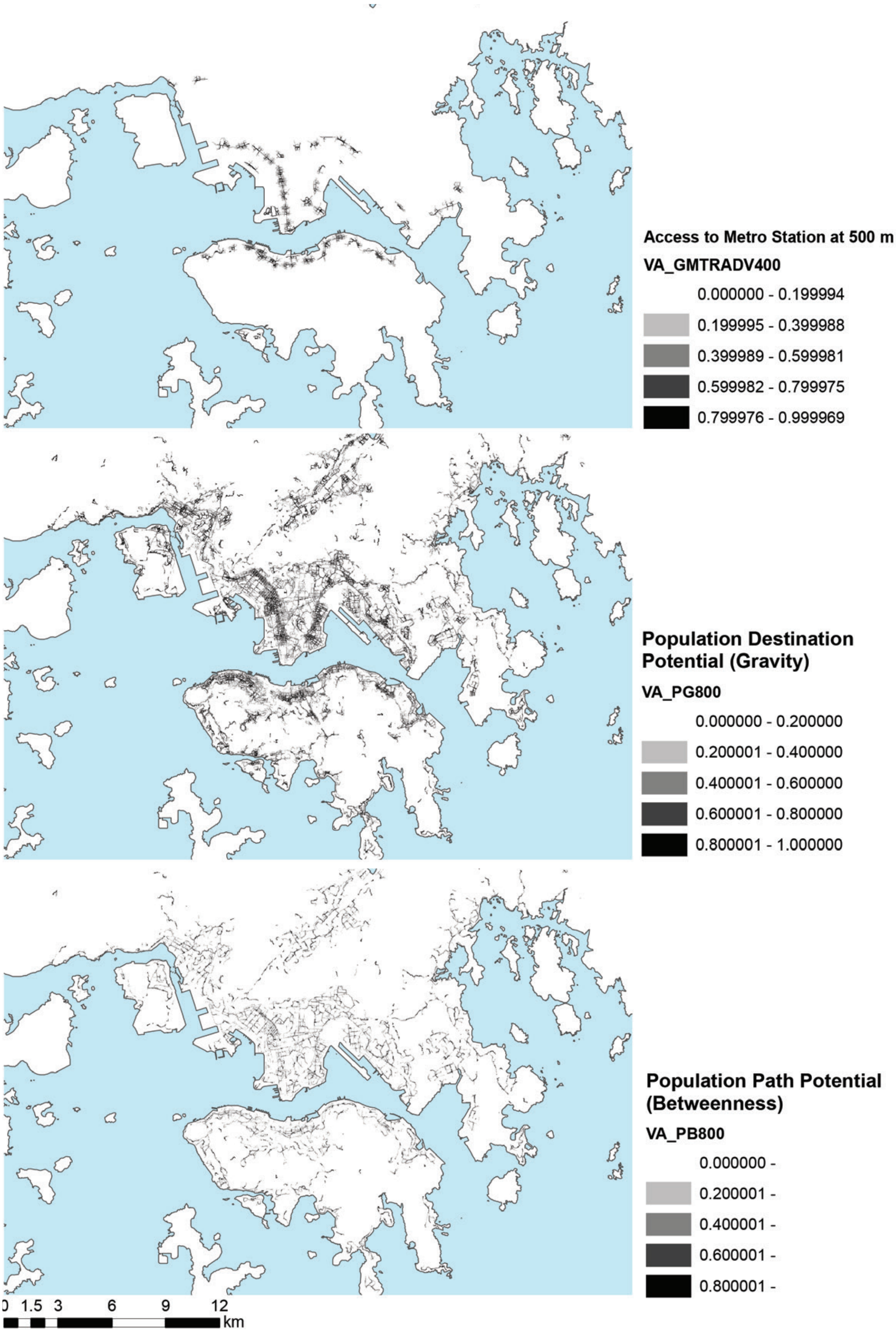


Figure 3.2.10. Evaluation criteria: access to metro station at 500m (top), population destination (middle) and path (bottom) potentials.

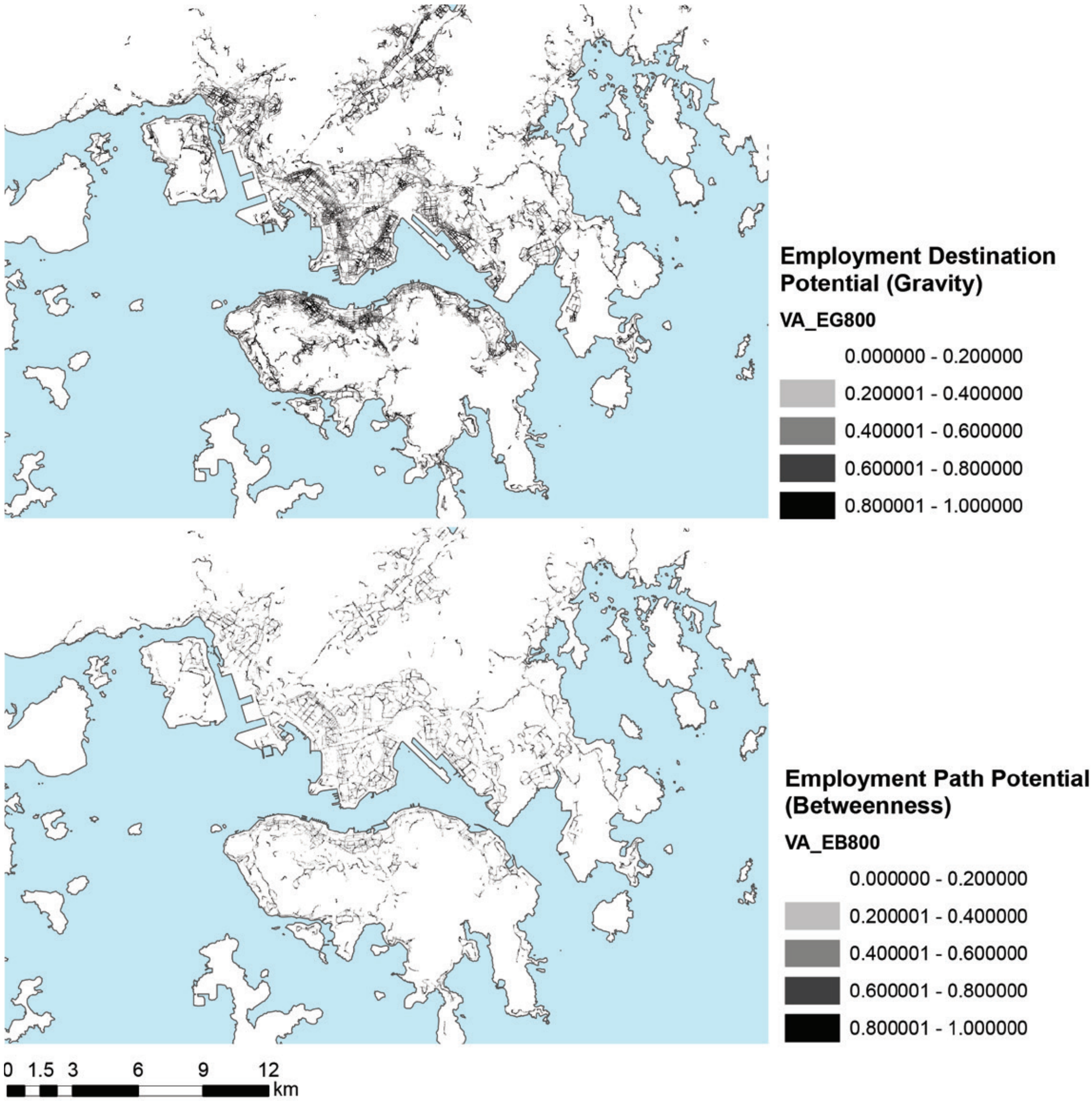


Figure 3.2.11. Evaluation criteria: employment destination and path potentials.

3.2.4. AHP and fuzzy qualifiers: Calculating relative importance of criteria and their aggregation according to attitudes towards uncertainty

Similar to San Antonio, the criteria were organized into a hierarchy (Figure 3.2.12). The criteria were divided into two groups: geomorphology and urban centrality. The geological and topographical group includes criteria related to the suitability of a location for underground construction, according to the properties of the ground itself. The topological group addresses the criteria related to the relationship of a particular location to all others within the existing urban morphology and distribution of MTR stations, resident population densities and employment densities.

Whereas the relative importance of urban centrality could be addressed through empirical evidence (see section 3.1.2.5), the geological and topographical criteria rely on tacit knowledge. A questionnaire was drawn up to elicit responses to pairwise comparisons between the criteria, asking "For a given site and everything else equal, is it more favorable (for a basement development scenario) to be…" to first identify the more important factor between the two and then providing a Likert scale from 1 to 9 asking "how much more favorable is it?" (see Appendix 3.2.1). The three members of the team who responded gave very different answers (Table 3.2.4). The third member's answers were discarded due to inconsistency in the responses (consistency index of 0.98 for a permissible cutoff of 0.1).[27]

The comparison matrices of experts 1 and 2 were combined to form a single matrix (Table 3.2.5), adjusting for inconsistency so that expert 2's evaluation (CI = 5%) was given higher weight than that of expert 1 (CI = 38%), resulting in a matrix with a consistency index of 6% and a priority vector placing slope as having the highest contribution to underground potential, followed by existing infrastructure, a near tie between floods, aggregate and the amount

Table 3.2.4. Rankings of geological and topographical criteria resulting from pairwise comparisons by three experts.

Criteria	Ranking (Expert 1) (geologist)	Ranking (Expert 2) (civil engineer)	Ranking (Expert 3) (geologist)
Existing underground infrastructure	6 (6%)	2 (22%)	6 (2%)
Zones of past major floods	3 (17%)	4 (10%)	5 (16%)
Geology suitable for aggregate	5 (8%)	3 (15%)	1 (29%)
% of soft ground in first 30m	2 (24%)	5 (6%)	2 (21%)
% of corestones in first 30m	4 (8%)	6 (3%)	4 (16%)
Slope	1 (37%)	1 (44%)	3 (17%)
Consistency indexes	38%	5%	98%

[27] Time did not unfortunately permit redoing the pairwise comparisons again after discussing the points of dissensus with the team. It was thought that the third expert might have been thinking sometimes in terms of cavern development and sometimes in terms of basement development, which could explain the extreme inconsistency.

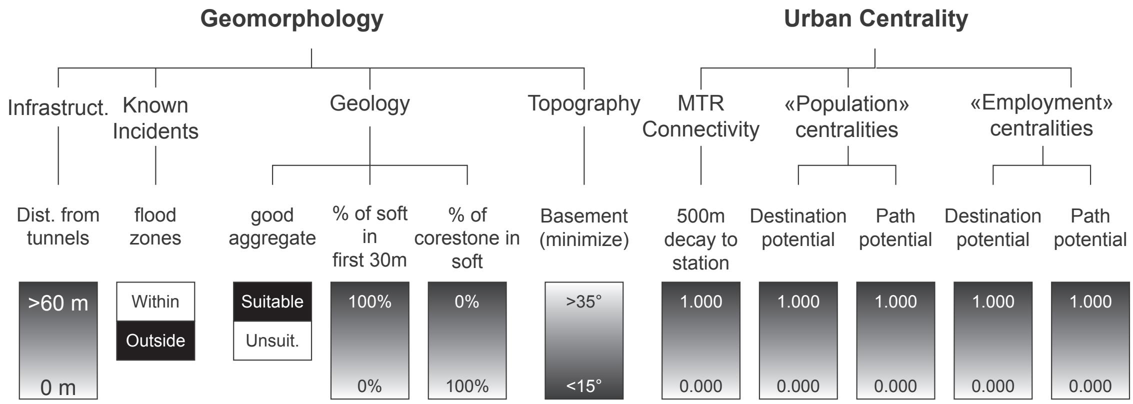


Figure 3.2.12. Geomorphological and urban centrality criteria considered for evaluation of underground non-cavern potential.

Criteria	Infra.	Floods	Aggreg.	% Soft	% CS	Slope	Priority Vector (%)
Existing infrastructure	1.00	1.47	1.86	1.93	3.62	0.22	**15**
Floods	0.68	1.00	0.46	1.25	3.42	0.16	**10**
Aggregate	0.54	2.16	1.00	1.25	2.43	0.13	**11**
% Soft	0.52	0.80	0.80	1.00	2.48	0.38	**10**
% Corestones (CS)	0.28	0.29	0.41	0.40	1.00	0.12	**4**
Slope	4.57	6.17	7.53	2.60	8.31	1.00	**49**

Consistency index = 6%

Table 3.2.5. Comparison matrix of geological and topographical criteria for experts 1 and 2, weighted according to the consistency of their responses.

of soft ground in the first 30 meters, with the influence of corestones as negligible (at a contribution of 4%).

The aggregation of the layers was performed at both global and local scales. Global aggregation combined all eleven criteria using the priority vectors for geological and topographical criteria as well as those for the accessibility metrics (Figure 3.2.13). These were first aggregated in a risk-neutral scenario, corresponding to equal consideration for all criteria weights (α = 0.5, see section 3.0.2.3), then for a risk averse (α = 0.9) and a risk-taking (α = 0.1) scenario. The local aggregation scenarios organized the aggregation process a bit differently (Figure 3.2.14). The geological and topographical criteria were separated into a group for which a 'local' neighborhood made no sense: distance from tunnels, aggregate suitability and flood zones. For these criteria a location is either within or outside of a specified distance. For the criteria concerning soft ground, corestones and slope, one location may do better than another in a particular geographical subunit, even if its potential is not high globally. In order to reflect the average diameter of territorial planning units (the scale at which decisions are made) and to be consistent with the accessibility metrics, a neighborhood of 800 meters was adopted for these three criteria. For the accessibility metrics, the accessibility to MTR did not make sense as a local metric, while the four population and employment metrics were also given a neighborhood size of

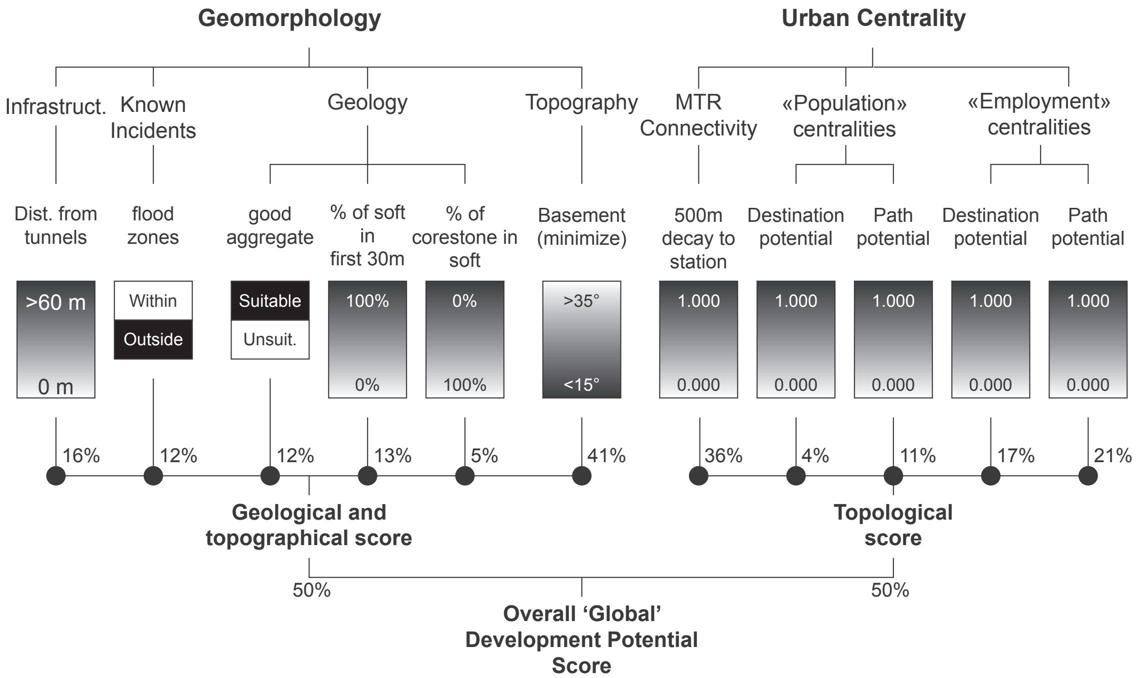


Figure 3.2.13. Aggregation weights and hierarchy for 'global' potential

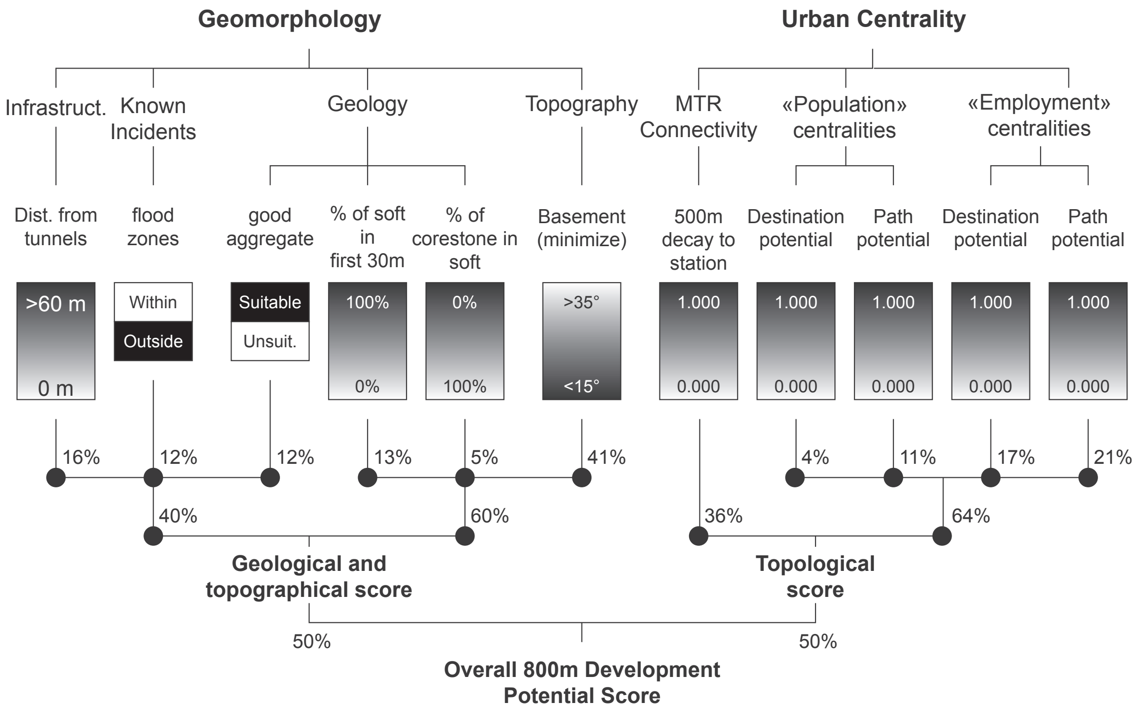
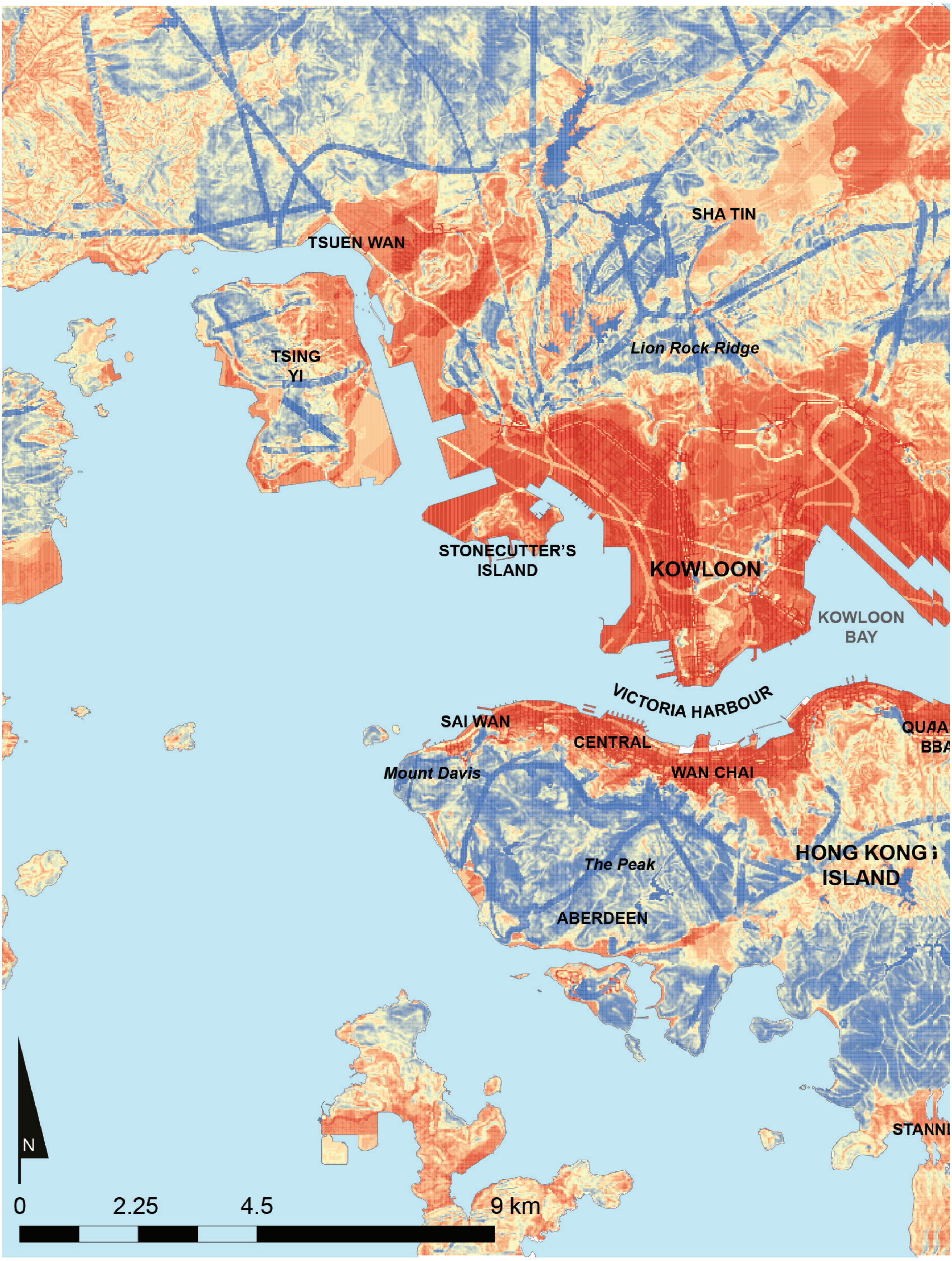


Figure 3.2.14. Aggregation weights and hierarchy for 800m potential score

800 meters. Local metrics were also aggregated using fuzzy qualifiers for calculating potential with respect to varying attitudes towards risk. When combining the topographical/geological and topological sets of criteria, they were given equal importance for both local and global maps.

3.2.5. Results: Hong Kong Underground Potential

The global risk-neutral aggregation highlights the areas where underground potential is highest (Figure 3.2.15). This includes most of the reclamation areas around the Kowloon promontory and along the northern shore of Hong Kong Island from Kennedy Town to Central and Quarry Bay and the areas to the northeast of Sha Tin and around Tsuen Wan where the topography is relatively flat. Indeed, the importance of slope is evident: Kowloon is characterized by areas where the basement potential decreases substantially on local hillsides. Potential also drops within the buffer zone around existing infrastructure, which appear clearly on the map and follow much of the underground rail and road tunnels. The highly centrality metrics for road segments show up at the small scale and serve to reinforce potential where roads are central to resident population density and to density of employment.


TSUEN WAN
SHA TIN
TSING
YI
Lion Rock Ridge
STONECUTTER'S
ISLAND
KOWLOON
KOWLOON
BAY
VICTORIA HARBOUR
SAI WAN
CENTRAL
WAN CHAI
Mount Davis
HONG KONG
ISLAND
The Peak
ABERDEEN
N
0
2.25
4.5
9 km

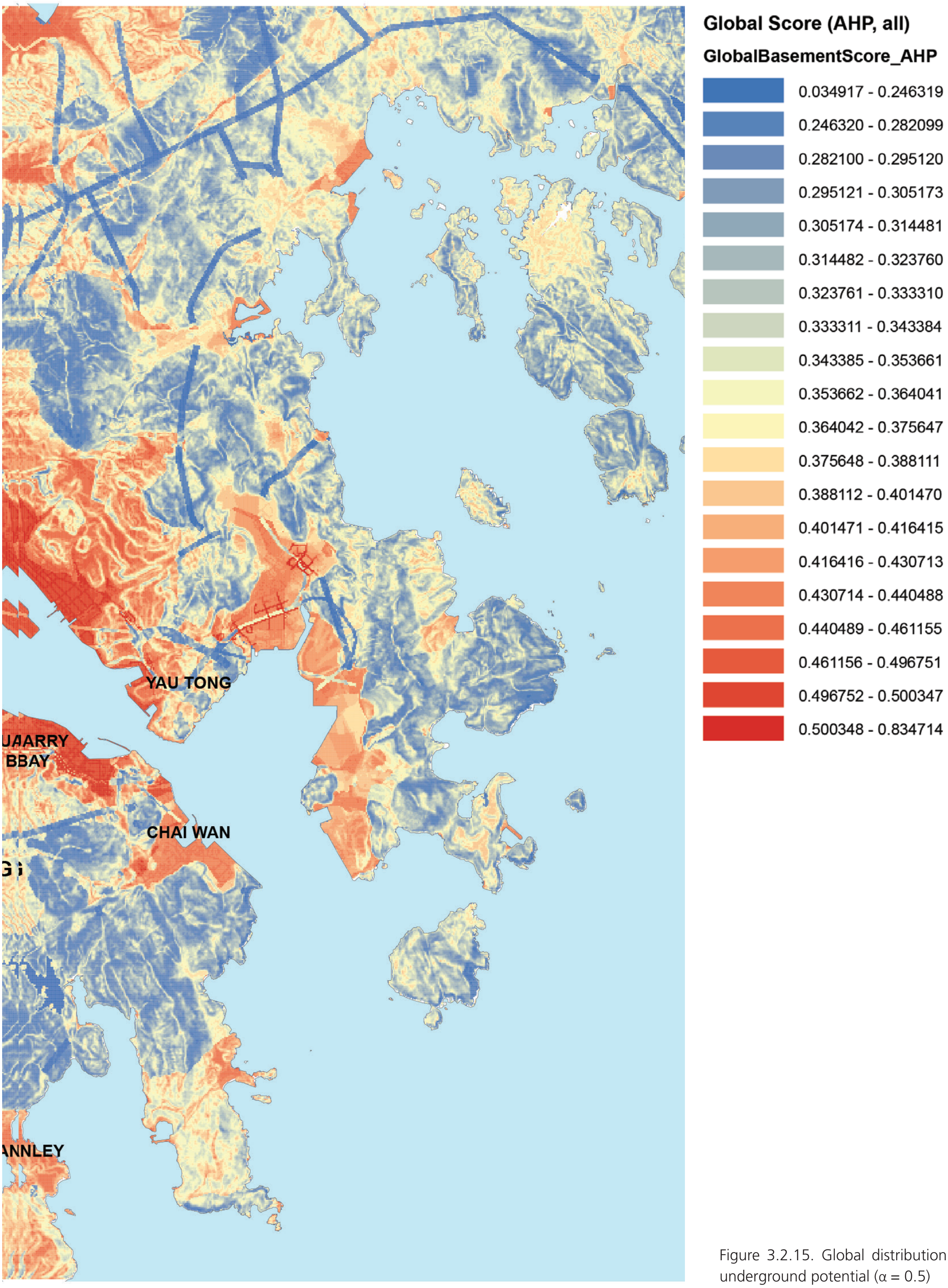


Figure 3.2.15. Global distribution of underground potential (α = 0.5)

When aggregating the criteria according to a risk-taking attitude, almost the entire areas is assigned a high underground potential score (Figure 3.2.16, top). This is clearly an anomaly related to the ordering of criteria. When several criteria are binary (0 or 1), the ordering algorithm will place all values equal to one at the top. Because nearly every location has a value of 1 for at least one criterion (being outside of flood zones for instance), this raises the overall potential in a way that is misleading. This is a disadvantage of using binary variables and one that will have to be tested in future case studies.

When overweighting the lowest criteria (in a risk-averse scenario) (Figure 3.2.16, bottom), the areas of highest potential lie in flat areas of easy excavation outside of corestone zones and the buffer area around existing infrastructure. The locations of highest potential are fewer than in the risk-neutral scenarios. There is very little potential observed outside of reclamation areas or areas where soft ground is unobstructed by corestones. As the maps are translated into prescriptive master plans or other land planning instruments, these areas would be the ones to prioritize if the decision-making climate is reluctant to deal with any adverse conditions in underground construction.

The risk-neutral aggregation in an 800-meter radius around map cells finds a similar distribution of potential as the global aggregation, but with several exceptions (Figure 3.2.17). Where potential calculated as relative to the whole Hong Kong SAR emphasizes mostly the reclamation areas of the main island, Kowloon, Tsuen Wan and Sha Tin, the 'local' aggregation picks out areas in between, like further in-land and at higher elevations. There are several flat areas that may be locally of interest for underground development. The local aggregation also allows for a greater differentiation at a smaller scale. To best illustrate this, it is useful to return to a particular case. The 2014 Policy Address announced a pilot study for strategic cavern development in four locations: Tsim Sha Tsui West, Causeway Bay, Happy Valley and the area around Admiralty and Wan Chai. A report released in early 2015 illustrated the precise boundaries of these strategic areas (Figure 3.2.18). Although these areas are slated for more basement style development, some of them lie near possible future cavern locations. An excerpt from the detailed cavern master plan (Figure 3.2.19) suggests that the Admiralty / Wan Chai and Causeway Bay areas are bordered by zones of medium to high cavern potential.

In preparing a presentation in September of 2015 to the members of the Geotechnical Engineering Office who had commissioned the various underground studies conducted by Arup, the Admiralty / Wan Chai and Causeway Bay sectors were adopted as an interesting demonstration of the complementarity between the cavern

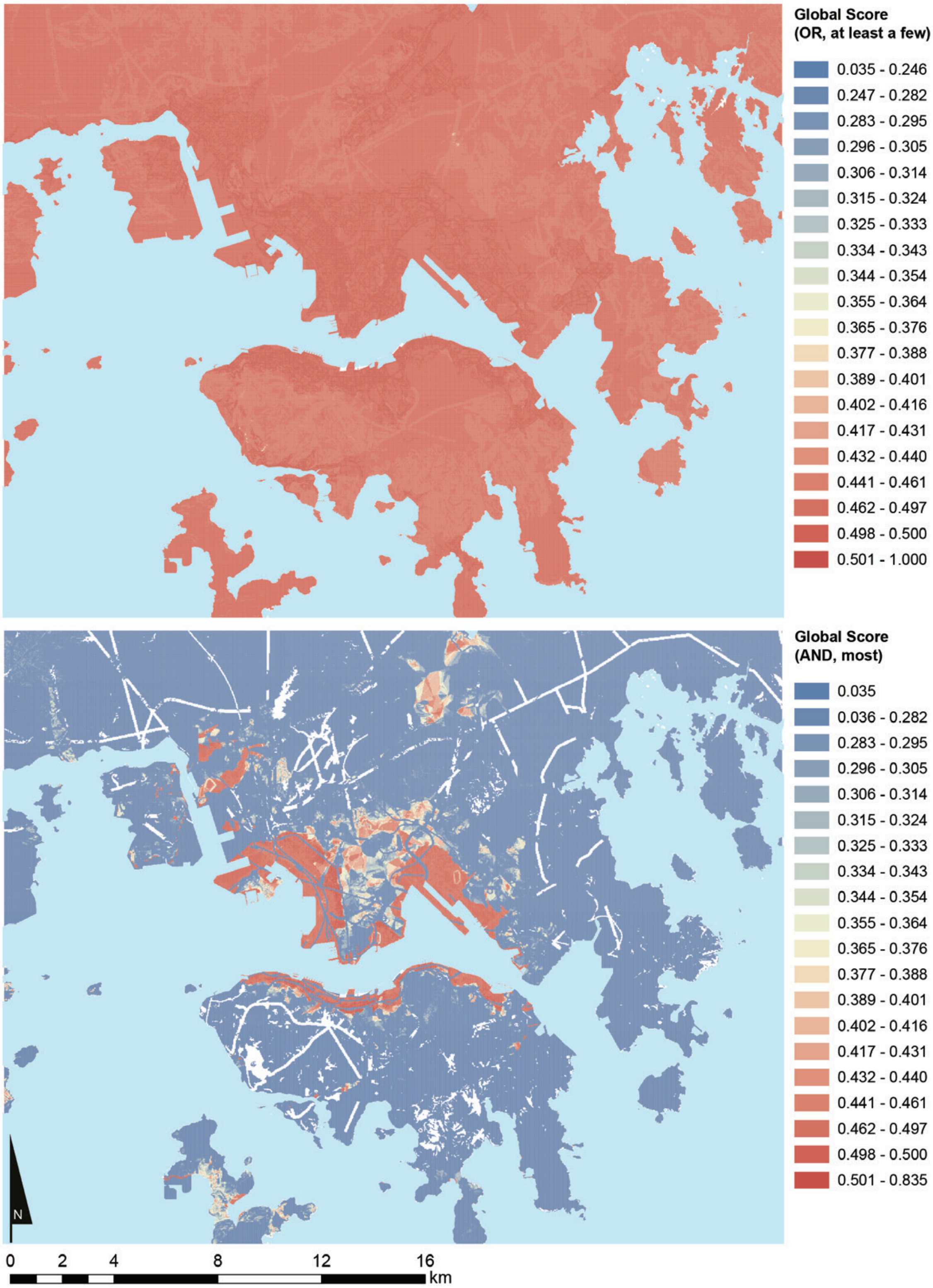
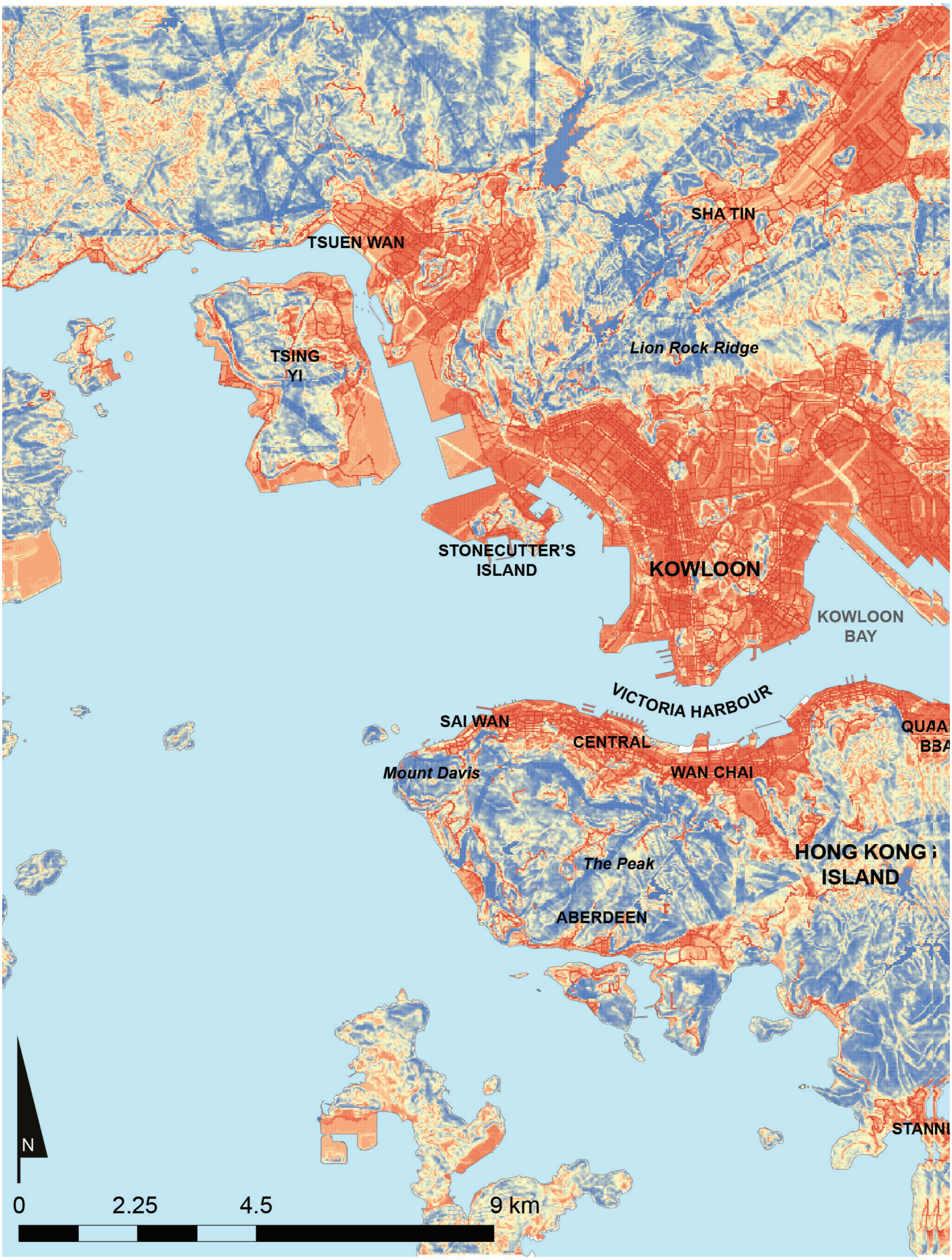


Figure 3.2.16. Global risk-taking (alpha = 0.1) and risk-averse (alpha = 0.9) aggregation scenario.


TSUEN WAN
SHA TIN
TSING
YI
Lion Rock Ridge
STONECUTTER'S
ISLAND
KOWLOON
KOWLOON
BAY
VICTORIA HARBOUR
SAI WAN
CENTRAL
WAN CHAI
Mount Davis
The Peak
ABERDEEN
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0
2.25
4.5
9 km

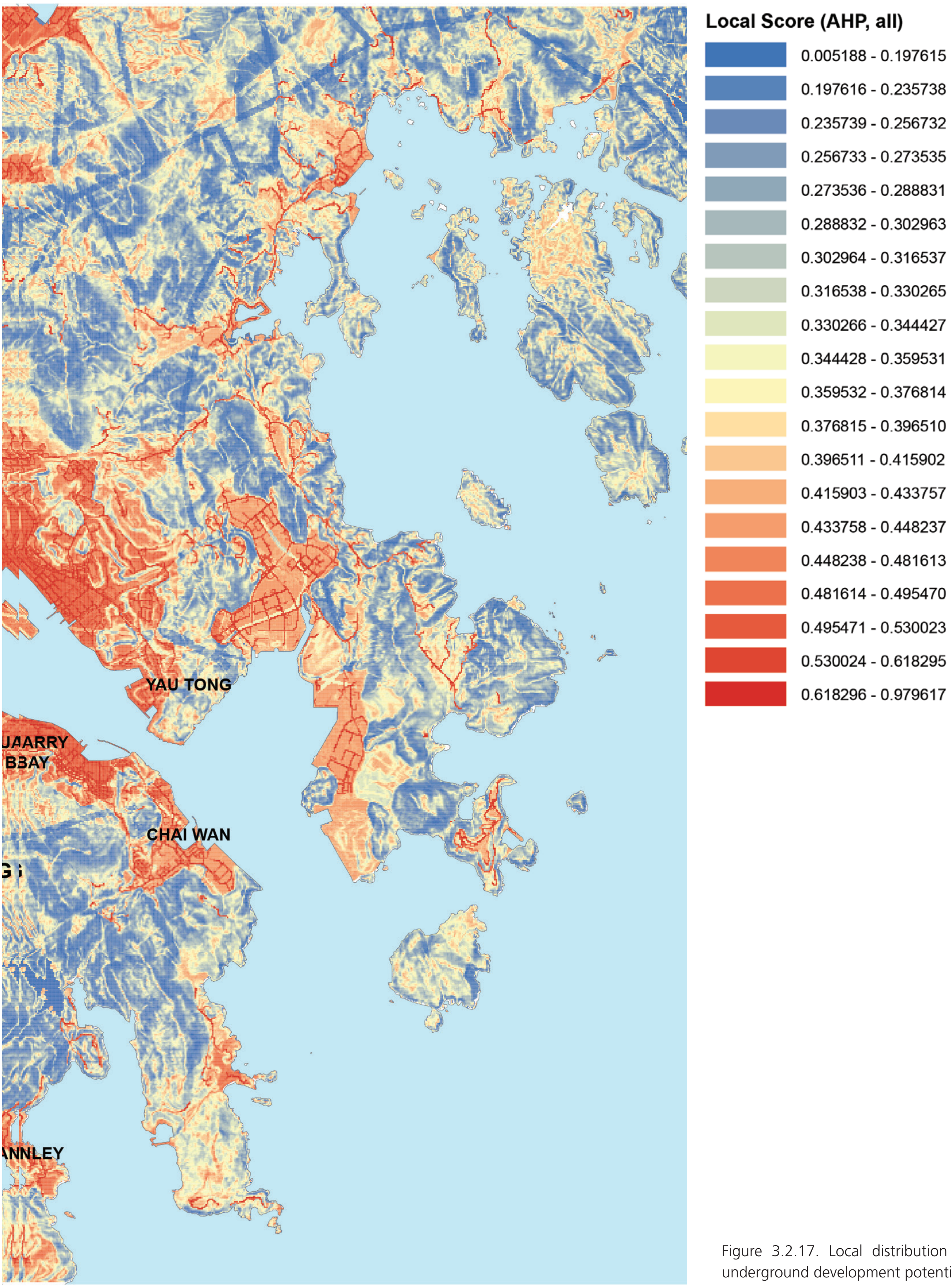


Figure 3.2.17. Local distribution of underground development potential

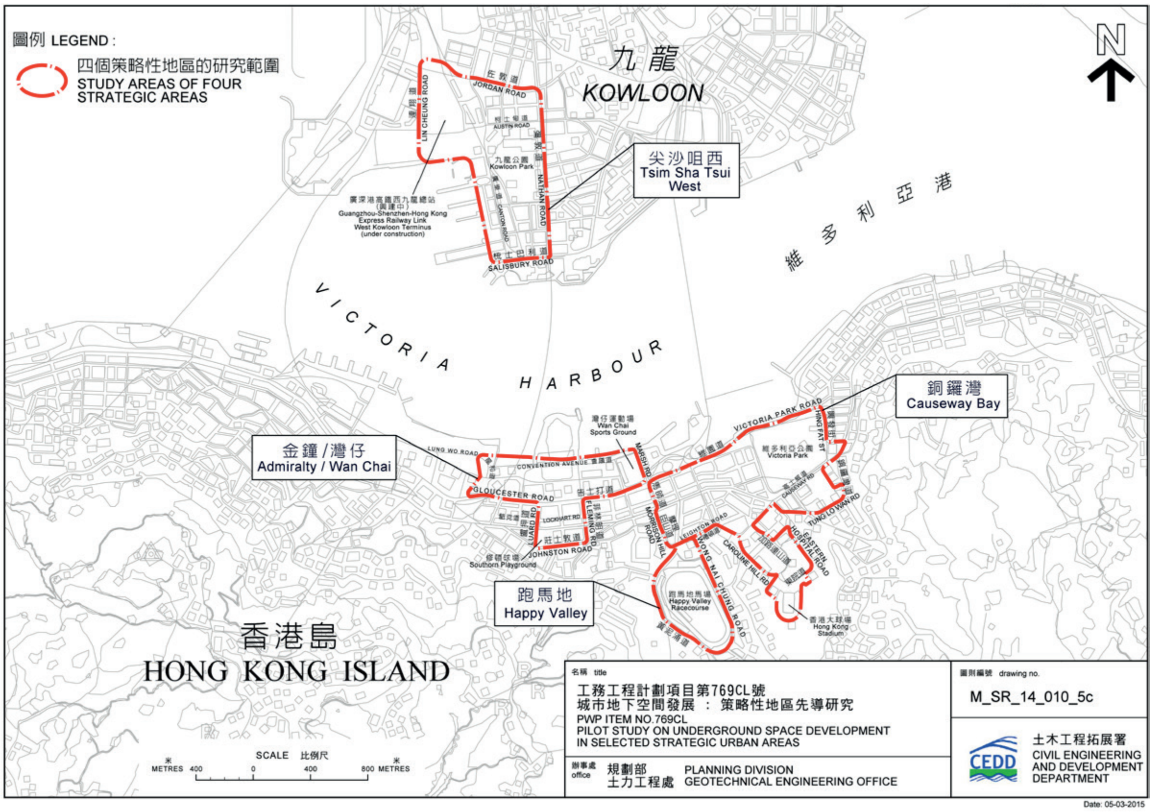
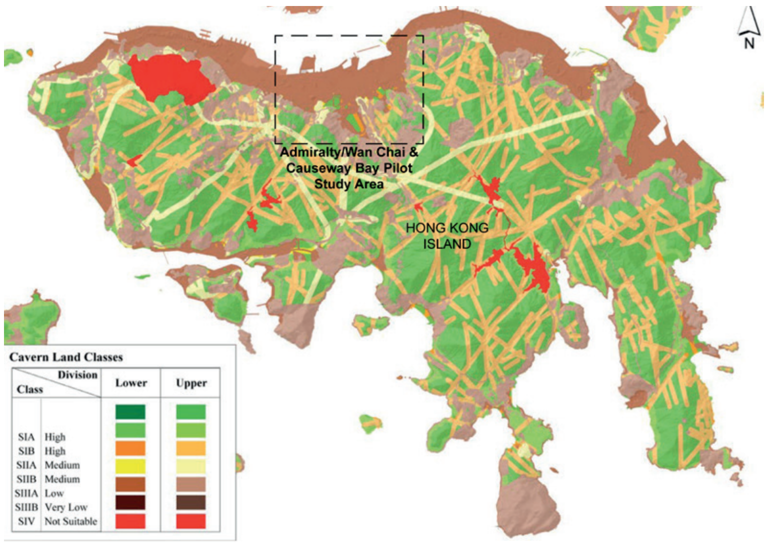


Figure 3.2.18. Strategic Urban Areas for Underground Space Development (source: Legislative Council of Hong Kong, 2015).

Figure 3.2.19. Admiralty / Wan Chai and Causeway Bay study area overlaid on the cavern master plan (source: Arup)



suitability study and the Deep City basement potential plan.[28] The risk-neutral evaluation of potential of this area (Figure 3.2.20) shows the distribution of the urban form and its proximity to the cavern area. It is clear that much of the developed areas are located on relatively level ground down both along the coastline and inland at higher elevations. An oblique aerial photo extracted from Google Maps and zooming in on the zone around Causeway Bay and Victoria Park (identified in Figure 3.2.19) does better justice to

[28] Although the same location will be taken as an example here, the results are not the same as what was presented to GEO in 2015. The meeting resulted in some small modifications to the aggregation method. The analysis here will also go further than it did at the time.

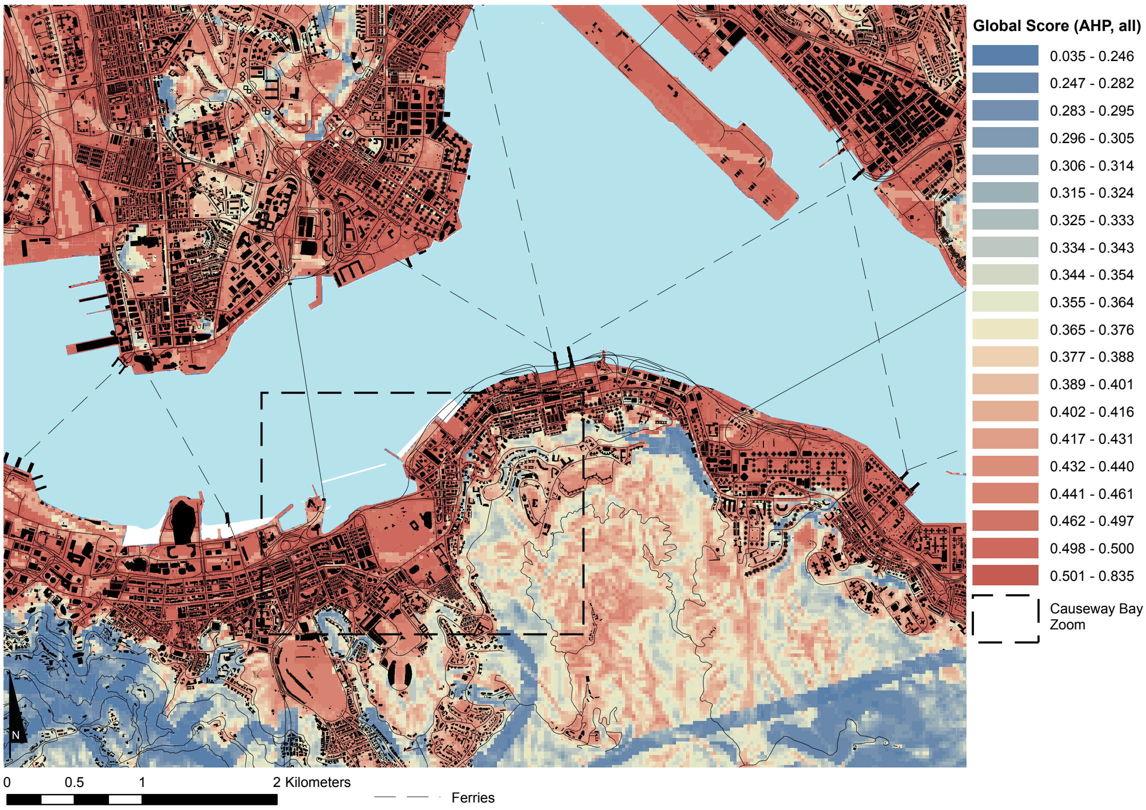


Figure 3.2.20. Underground development potential of south Kowloon and Northern Hong Kong Island around Causeway Bay.

this landscape of high density next to a mountainous, but wooded, terrain (Figure 3.2.21).

Although perhaps not obvious in these images, one of the challenges facing cavern development anywhere in Hong Kong is how to link the new development to the existing urban fabric. Street networks and paths tend to follow existing hierarchies of activities and these are not often located on the circuitous paths up hillsides. A closer zoom on this area of Causeway Road and Victoria Park near the possible cavern area (Figure 3.2.22, (a)) shows at least two roads that follow the contours higher up the mountain. Access to the cavern would not likely occur from Causeway Road itself because of existing land developments. The portal entry to the cavern would have to be either on Yee King Road or lower on Tin Hau Temple Road. Tin Hau Temple Road is located nearer to zones with high underground potential in both a risk-neutral and risk-taking scenario (Figure 3.2.22 (a) and (b)), but in a risk-averse scenario ((c)), its potential drops significantly. This is in part due to the fact that it is slightly peripheral and not directly linked to Causeway Road. The challenge is even more evident for Yee King Road. Its underground potential is medium to low in all scenarios for attitudes towards risk and from the aerial photo it is clear that it is not a path that will attract many passersby. This problematic is an interesting one for urban designers, as the descriptive and diagnostic master plan meet with more prescriptive forms of volumetric master planning.

Figure 3.2.21. The Causeway Bay area looking down Causeway Road towards the East . Dense urban development wraps around the base of the mountain with high cavern suitability (source: Google Maps).

Yee King Rd
如心銅鑼灣海景酒店
Shing Loong Court
Chinese Rhenish Church - Wanchai
中華基督教禮賢會灣仔堂
Queen's College Old Boys' Association
皇仁書院舊生會
Lin Fa Kung Temple - Tai Hang
大坑蓮花宮
Lai Tak Tsuen
Tak Chuen Lau
Illumination Terrace
光明臺
Lai Tak Tsuen

Figure 3.2.22. The Causeway Bay area around Victoria Park adjacent to a potential future cavern

3.2.6. Opportunities for future work and conclusion

When the preliminary results of Deep City Hong Kong were presented to representatives from the Geotechnical Engineering Office (GEO), they appreciated the fact that each location on the map was given a number. This number was perceived as a form of quantitative evidence of potential and permitted a numerical comparison of two different sites. Indeed, this has been one of the ongoing achievements of the Deep City method. But it can also be a risk if the numbers are taken as an unambiguous and absolute appreciation of potential. The overall potential score is the result of various stages of evaluation made by experts with privileged, but imperfect knowledge, and of estimations made of site characteristics based on interpolation of geological data. Once local geological (and socio-spatial) investigations are made on a particular site, its potential may increase or decrease accordingly.

Further work can nevertheless focus on making the practices by which these numbers are produced as rigorous as possible. As in the San Antonio case study, Deep City Hong Kong's use of the Analytic Hierarchy Process did not conduct a sensitivity analysis of the resulting priority vector, which would test the stability of the priority vector and the amount of change in evaluation that would be necessary for the criteria to change rank.[29] While the risk of a change in rank is probably not critical for a use of the AHP in situating elements on a relative scale (as opposed to comparing alternatives of which one and only one can be the best), sensitivity to change in rank could be evidence of an internal inconsistency in pairwise comparisons. The consistency index gives only a comparison matrix-wide evaluation of consistency and does not aide in finding the culprit criterion.

Other improvements to the mapping method concern the criteria adopted and the use of the centrality metrics in the local analysis. Several criteria that were used in the cavern study were dropped and never reconsidered for the underground 'basement' potential evaluation. These include faults and land fill areas, which would both create problems for underground construction. Although the cavern study took zoning into consideration, the basement alternative preferred to operate prior to zoning (which admittedly can be changed more than the geology or existing urban form). The centrality metrics are selected to capture the latent potential of the urban fabric, from which zoning can be evaluated. The analysis here focused on commercial spaces, because these non-NIMBY spaces are considered to concern investors and developers in addition to the population at large. The latent potential could, however, be considered differently for other types of uses. Data centers, sewage treatment plants or storage spaces engage with centrality differently.

[29] Thomas L. Saaty and Luis G. Vargas, "Sensitivity Analysis in the Analytic Hierarchy Process," in *Decision Making with the Analytic Network Process*, by Thomas L. Saaty and Luis G. Vargas, vol. 195 (Boston, MA: Springer US, 2013), 345–60, http://link.springer.com/10.1007/978-1-4614-7279-7_15.

Together, the cavern suitability plan and the basement potential plan constitute a reservoir of potential, rendering the geology and the urban morphology of Hong Kong a source for future movements, transformations and recoding. This chapter explored how the Deep City mapping method could accompany another procedure for establishing potential and how this underground potential could be complementary, creating new development opportunities for a city whose needs are pressing, but whose needs do not necessarily have to limit latent opportunities or guide the future planning process. Once the maps are in the hands of planners, they will be confronted with competing sets of interests and this underground potential will have to be managed as a limited resource. The maps (and their creators) therefore need to travel, to leave the GEO and CEDD for not only planning departments, but also universities. The volumetric future of Hong Kong will be made of a series of top-down initiatives informed by a strong bottom-up appropriation and recoding of spatial practices.

Chapter 3.3

Deep City Dakar

3.3.1 Conditions

Dakar is situated on the Cap Vert peninsula, on the western edge of continental Africa (Figure 3.2.1). The area from Cap Manuel and the port to the Yoff Plateau where the airport is situated to the north is known as the Cap. Its topography is the result of volcanic activity occurring several million years ago. The Yoff Plateau and the area including what is now called the Plateau and Cap Manuel are both 20 to 60 meters above sea-level, while the area between them, from Medina to the industrial areas south of Hann, is at an elevation of around two to seven meters. In this area, the soil is affected in the winters by humid conditions and occasional flooding. The geomorphology of the Cap reflects its volcanic past, with a 25-meter layer of basalt (volcanic deposits) sandwiched between several meters of more recent yellow sands and an on average 30-meter thick layer of sand beneath. Underlying the sands is a much thicker, older layer of clay and marl, which is at its lowest along the northern part of the Cap and gradually rises to several meters below the surface just north of the fault line separating Medina from the Yoff Plateau[1].

The Cap is joined to the continent by an isthmus composed mostly of sand and clay formations. The topography is similar to that of the Medina and the southern shore of Cap Vert, with elevations only several meters above sea level in some places. Along the northern coast, littoral sands mix with ancient sand dunes carried in by the wind from the continent. Like on the Cap, the isthmus lies above the same layer of clay and marl, which is anywhere from 20 to 50 meters below the surface. The sand formations of this part of Cap Vert contain a major freshwater aquifer, the quaternary sands

[1] Bernard J. Noël et al., "Carte Géologique de La Zone D'activité Du Cap-Vert À 1/50000. Formations Du Substratum," Map (Dakar: GEOTER SAS, 2009); Bernard J. Noël et al., "Carte Géologique de La Zone D'activité Du Cap-Vert À 1/50000. Formations Superficielles," Map (Dakar: GEOTER SAS, 2009); Gilbert Crevola, Jean-Marie Cantagrel, and Christian Moreau, "Le volcanisme cénozoïqe de la presqu'île du Cap-Vert (Sénégal): cadre chronologique et géodynamique," *Bulletin de la Société Géologique de France* 165, no. 5 (1994): 437–46.

aquifer (*nappe des sables quaternaires*), also known as the Thiaroye aquifer (*nappe Thiaroye*). The proximity to sea level has resulted in several humid depressions known locally as *niayes* (from the Wolof word designating this area). Of the areas of human settlement on the isthmus, the municipalities of Pikine and Guédiawaye are probably the most well-known.

The quaternary sands aquifer, due to the permeability of the sand formations, keeps the region of the *niayes* humid almost year-round. Like the lower-lying areas from the western coast of the Cap through Medina and up to Hann, this part of the isthmus is regularly affected by flooding. During periods of heavy recharge, either due to rain or rising aquifer levels due to a decrease in groundwater extraction through pumping, a large portion of the region is flooded.[2] This communicability of the water from surface to subsurface also increases the aquifer's vulnerability to pollution from runoff and informal dumping of waste that occurs regularly in the zones of the *niayes*. The quaternary sands aquifer is not the only aquifer found on Cap Vert. On the Cap, in particular beneath the Yoff Plateau, the sands beneath the basalt formations contain a body of freshwater known as the infrabasaltic sands aquifer (*nappe des sables infrabasaltiques*) (Figure 3.3.2, 6). As opposed to the quaternary sands aquifer, the infrabasaltic sands aquifer is cut off from surface recharge by the lower permeability of the volcanic deposits.[3]

European settlement began in Dakar first on the island of Gorée in the 17th century. Important in the network of slave trade for the New World up until the beginning of the 19th century, the European colonization did not move onto the mainland until the French decided to occupy the peninsula for the development of agriculture and commerce, in particular peanuts. The city of Dakar was founded on Cap Vert across from Gorée in 1857, with the development of the port by 1866. If Gorée was part of the maritime transport of slave labor, the port of Dakar added shipments of agricultural goods to the networks of ports that included at the time Rufisque (now an exurb of Dakar), Saint-Louis (the capital of Dakar north towards the border with Mauritania) and a port at the mouth of the Saint-James River in Gambia. With the development of the rail lines linking Dakar to Saint-Louis in 1885 and then to the inner country in 1923, the port of Dakar gradually surpassed the others in terms of economic importance.[4]

The processes that fueled Dakar's growth in the 20th century were military, commercial, administrative, cultural-political and geographic.[5] During the height of the French colonies in West Africa,

[2] Centre de suivi écologique, "Rapport sur l'état de l'environnement au Sénégal" (Dakar: Centre de suivi écologique, 2010).

[3] Jean-Paul Barusseau et al., "Notice explicative de la cartographie multi-couches à 1/50000 et 1/20000 de la zone d'activité Cap-Vert" (Dakar: Ministère des Mines, de l'industrie et des PME, Direction des Mines et de la Géologie, 2009); Crevola, Cantagrel, and Moreau, "Le volcanisme cénozoïqe de la presqu'île du Cap-Vert (Sénégal): cadre chronologique et géodynamique."

[4] A. Sinou, "Dakar. Bulletin d'information Architecturales" (Paris, Institut Français d'Architecture, 1990).

[5] Yvon Mersadier, "Dakar, Entre Hier et Aujourd'hui," *Revue Française D'études Politiques Africaines: Le Mois En Afrique*, no. 29 (1968): 39–50.

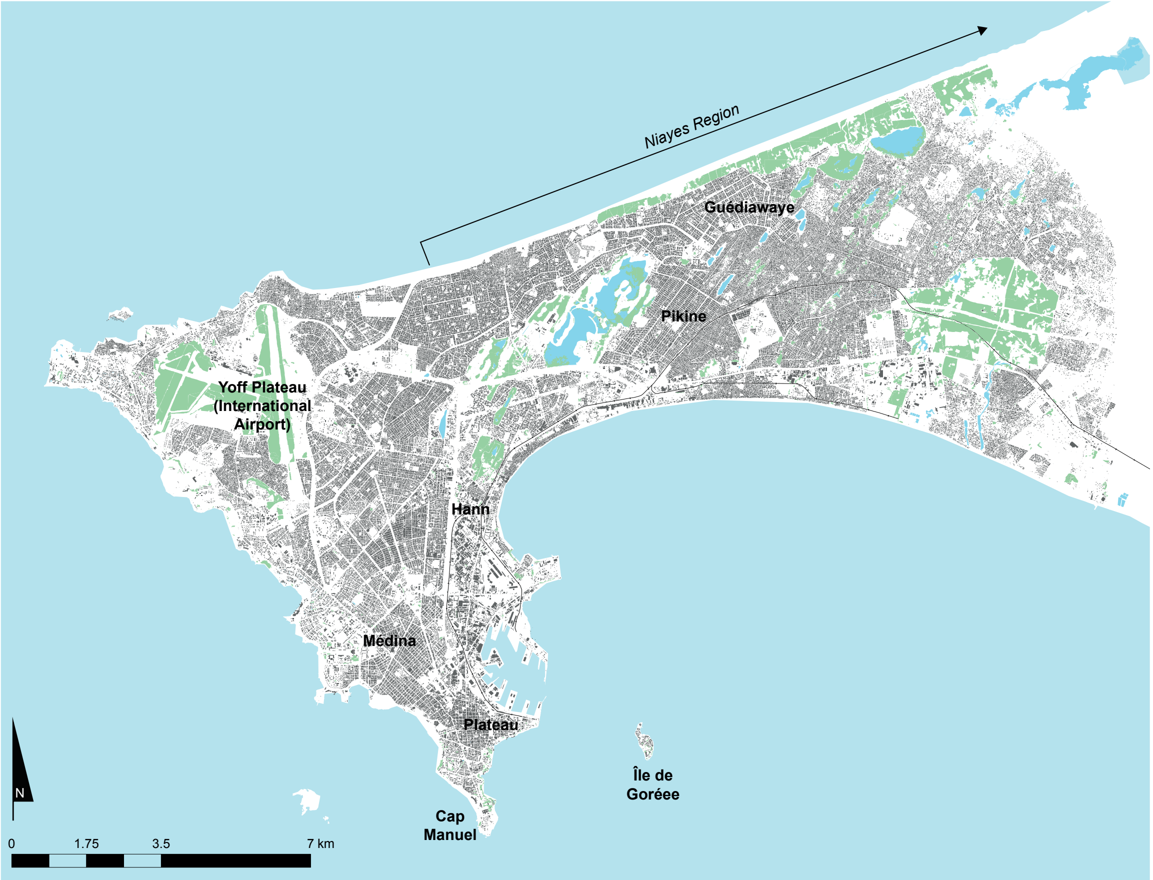


Figure 3.3.1. The Cap-Vert peninsula from Gorée to Cap Manuel, the Yoff Plateau to the isthmus connecting the Cap to the continent.

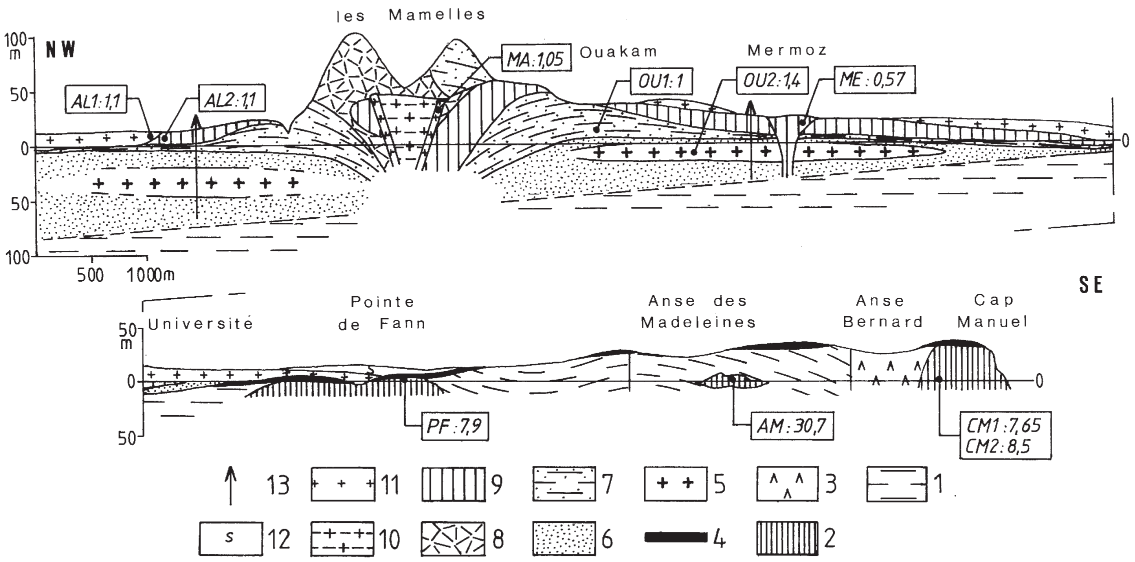


Figure 3.3.2. Geological section from the north of Yoff to Cap Manuel in the south, passing through Les Mamelles. 1 – Sedimentary tertiary; 2 – Tertiary lavas; 3 – Tertiary tuffs; 4 – Ferrugineous cuirass; 5 – Medium volcanic ensemble; 6 – Infrabasaltic sands; 7 – Volcanic surge deposits; 8 – Strombolian scorial; 9 – Streams of hawaiite; 10 – Streams of doleritic hawaiite in lava lakes; 11 – Streams of doleritic hawaiite; 12 – Recent sands; 13–Boreholes (source: Crevola et al., 1994: 442).

Dakar was an important military location for defending French interests. Once Dakar's modern port was completed at the end of the 19th century, Dakar's commercial importance gradually eclipsed that of Rufisque for the peanut industry. Dakar was not only the city of country, but of a continent—in 1895, it was declared the capital of French West Africa (*l'Afrique occidentale française*). The local policies of the French also transformed the identity of the native Senegalese living in Dakar, who were given French citizenship and even elected a representative to the French parliament. The inhabitants of Dakar, with their attention turned to modern Europe and France, gradually lost interest in the rest of the country. The important role of Dakar in the international movement of goods and people would eventually take on a new scale with the development of the Yoff airport. As the point of Africa closest to the Americas, Dakar was (and for some airlines still is) a place to stop and refuel on the way to the inner and southern parts of the continent.

The growth and transformations of the urban fabric of Dakar have been both caused and conditioned by these processes. In the early 20th century, settlement in Dakar was mostly centered on the administrative area of the present-day Plateau and the port to the north. Following the Second World War, the first plan for all of the Cap-Vert peninsula was drawn up by the French government, with the motivation to strengthen the military presence of the French in West Africa. Many of the roads linked military installations located along the coast, including Cap Manuel and an airport (closed in 2011) at Ouakam on the Yoff plateau. The rail lines continue to supply the port with goods for export. The political status and cultural practices of the local Senegalese proved a challenge for any large-scale urban planning operation. As French citizens, the native populations had a strong negotiating power, which complicated processes of land acquisition and expropriation. The conflation by European urban planning in the early 20th century of hygiene and city form rendered incompatible European neighborhoods with those of the local Lebou. Following an outbreak of the plague in 1914 and 1915, the settlement of Medina was created in the lower elevations between the two plateaus to group the members of Lebou villages whose practices were considered incompatible with those of the European neighborhoods.[6]

The development of Dakar following the wars encouraged an influx of population, which required modifications to the 1946 plan in 1961. In particular, this plan dealt with the expansion of the urban area into the agricultural zones of the *niayes* on the isthmus.[7] Already in 1952, the city had to respond to unexpected population growth in the creation of Dagoudane-Pikine, which received a part of the population living in Medina.[8] By the end of the 1960s, several

[6] Assane Seck, "Dakar, Métropole Ouest-Africaine," *Mémoires de l'Institut Fondamental d'Afrique Noire*, no. 85 (1970): 1–516.

[7] Ibid.

[8] Marc Vernière, "Pikine, 'ville nouvelle' de Dakar, un cas de pseudo-urbanisation," *L'Espace géographique*,

years after Senegal's independence, the urban structure of Greater Dakar was composed of Dakar-Ville with its historic administrative function, the residential and commercial areas of Grande-Medina and the area of Grand Dakar, which was the most populated area, with both residential *cités* flanked by slums. The suburbs at the time included Ouakam, Yoff, Ngor, Amadies, Cambérène and Pikine. Ouakam and Cambérène were the result of industrial and military installations attracting a local population. Yoff, Amadies and Ngor were developed as residential neighborhoods. Pikine, along with Grand-Medina and Grand-Yoff were the result of displaced populations from the urbanized areas of the city center.

In the 1980s, an economic crisis saw the end of an urbanism guided by large projects to one oriented towards management.[9] For matters of housing, for instance, the state began delegating responsibility of housing development to private initiatives, which tended to build for the middle and upper classes. The masterplan of 1980, mandated to a private firm (SONED-BCEOM) by the Ministry of Urbanism, Habitat and the Environment. This plan was, however, only a framework for discussion and consultation and was based on a diagnostic that by the mid-1990s was already out of date.[10] Urban decision-making is increasingly fragmented. Since the elimination of the Dakar Urban Community (*La communauté urbaine de Dakar*) in 2000, there has been no coordinated city-wide planning effort to manage regional infrastructure in Dakar. Planning policies are elaborated by the government in Saint-Louis and center around the drawing up of urban planning documentation country-wide (including Dakar, the creation of special planning zones (ZAC: *zones d'aménagement concerté*), the control of land uses and the restructuring of neighborhoods, in particular 'informal' neighborhoods (*quartiers spontanés*).

Within the changed planning context, the drawing up of a new masterplan was coordinated by the Cities Alliance Project and published in 2010 as Dakar Horizon 2025.[11] An initial diagnostic remarked that the areas of highest population density (notably Medina and Pikine-Guédiawaye) are also the most negatively affected by flooding. Flooding is not only due to rainwater, but also results from a rise in groundwater tables after extraction of the quaternary sands aquifer was stopped when the water was no longer deemed potable. The 2025 plan proposes to recommence pumping for use for urban agriculture and to move populations in areas at risk. The transportation infrastructure (deemed sorely inadequate) is the backbone for the masterplan, which seeks to reorganize the territory into a polycentric network of multifunctional urban hubs—notably

no. 2 (1973): 107–26.

[9] Sinou, "Dakar. Bulletin d'information Architecturales."

[10] Jérôme Chenal, "Urbanisation, Planification Urbaine et Modèles de Ville En Afrique de l'Ouest: Jeux et Enjeux de L'espace Public" (PhD in Architecture, City, History, École polytechnique fédérale de Lausanne, 2009).

[11] Cities Alliance Project, "Stratégie de développement urbain du Grand Dakar (Horizon 2025)," Urban Masterplan, (2010).

Dakar, Pikine-Guédiawaye and Rufisque. If Dakar is a hub for commercial and service sector activities, Pikine and Guédiawaye are hubs for cultural and sports amenities.

Horizon 2025 met with criticism. First, it was deemed disconnected from the actual needs of the population, particularly for not having integrated local actors and citizens more into the visioning process. A review of the press revealed that questions of crime, the disappearance of public spaces due to the privatization of land were concerns that were not present in the plan. The creation of green areas and parks did not respond to concerns about the preservation of open spaces in urbanized areas and the protection of these open areas from privatization and informal parceling.[12] Following two severe floods in 2009 and 2012, the management strategies proposed by the masterplan proved superficial. A report by the Municipal Development Agency (*l'Agence municipale de développement*) not only recommends resuming the pumping of the quaternary sands aquifer, but it also draws up a larger strategy for managing drainage in the region of the *niayes*. In the study, the agency proposes repurposing the *niayes* for permanent or temporary storage of rainwater and linking them to the sea with a series of underground pipes or surface canals. Land use restrictions around the *niayes* would have to be rendered stricter, but could be supported by creating public recreational and leisure spaces in order to prevent informal occupation of the buffer zones.[13]

In 2014, the Senegalese government commissioned the Japanese International Cooperation Association (JICA) to prepare a revision of the 2010 masterplan, expanding the scope to 2035. The update was deemed necessary not only to respond to the inadequacies and omissions of the 2025 plan, but also to respond to unexpected population growth and climate change reports evaluating Dakar at risk for rising sea levels. Priorities for 2035 include the protection of open and green spaces from urbanization, promote thermal regulation measures in heat islands of the city and protect the coast from erosion. Their diagnosis identifies as existing problems the lack of a good public transportation network, the cost and unreliability of the electricity system, the regular incompatibility of land uses (industrial next to residential) and the low proportion of use of renewable energies like photovoltaic and hydroelectricity.[14]

JICA's preliminary report on the advancement of Horizon 2035 adopt as an overarching concept "*Dakar, une ville d'hospitalité*" (Dakar, a friendly (or welcoming) city). Their plan draws a parallel between hospitality and communicative potential through the

[12] Chenal, "Urbanisation, Planification Urbaine et Modèles de Ville En Afrique de l'Ouest: Jeux et Enjeux de L'espace Public"; Cities Alliance Project, "Stratégie de développement urbain du Grand Dakar (Horizon 2025)."

[13] Agence de développement municipal, "Plan directeur de drainage pluvial," Final Report, Étude de plan directeur de drainage (PDD) des eaux pluviales de la région périrubaine de Dakar (Dakar: Agence de développement municipal, 2012).

[14] Agence japonaise de coopération internationale (JICA), "Projet du plan directeur d'urbanisme de Dakar et ses environs Horizon 2035," Interim report (Dakar: Ministère du Renouveau Urbain de l'Habitat et du Cadre de Vie, Répuglique du Sénégal, 2015).

ability to get around and to engage with others. Like Horizon 2025, it orients development around a strong hierarchy of transportation networks, recommending the integration of bus rapid transit and commuter rail into land use planning. It expands the limit of the urban area to the communes of Rufisque, Thiès and Mbour, to which it gives an important status of regional hubs. Where Pikine and Guédiawaye were given an almost local urban hub status in the 2025 plan, they are deemed of little potential for further urban development and relegated to zones of recreation and tourism as local urban centers, linked into the regional transport network as part of a transit-oriented development strategy. JICA's preliminary report highlights its 'success' in organizing regular weekly meetings with actors and stakeholders in order to garner support at all levels of society.

Although the Dakar Horizon 2035 revision to the 2025 masterplan has yet to be officially published, it is clear that the underground resource of greatest concern is groundwater, both in its conflicts (flooding) and synergies (source of drinking and irrigation water). There is no consideration of what happens to materials that are moved or extracted. The drainage master plan compiled by the ADM underlines the necessity of dealing with excavated materials and makes references to their use on site for infill or terracing.[15] As for built underground space, no specific projects are integrated into the master plan.[16]

3.3.2. Resource potentials of the Dakar geology

Grouping the geological formations into geotypes reveals 10 major and three minor families of similar formations (Table 3.3.1). Looking at the superficial geology, the major geotypes are constituted by the littoral sands (LS), covering the low-lying areas from Medina across the isthmus. The littoral sands are composed of sands similar to what is found on beaches. The mixture of argillaceous sand and gravel covering the basaltic deposits on the Yoff Plateau and Cap Manuel correspond to the plains alluvium (APA) geotype. The dune sands (geotype EOL) in the region of the *niayes* have a smoother surface than the littoral sands due to their having been wind-blown. Scattered among the depressions on the isthmus are palustrine deposits (geotype P), which lie at the bottom of humid and sandy areas. The substrate is composed primarily of marl (clay and lime), particularly along the isthmus on the eastern side of a major fault line. The presence of Paleocene and Eocene limestone from sedimentary transformations of the shell-based sands creates for an alternation of limestone and marl (geotype MC). The marl found on the Cap, from Hann to Medina and onto the Plateau of former Dakar-Ville is only a mixture of Paleocene clay and marl (geotype M). Geological

15 Agence de développement municipal, "Plan directeur de drainage pluvial."

16 There is a project under construction as of August 2016 for an underground parking beneath the Place de l'Indépendence on Dakar-Plateau : http://www.villededakar.org/pages/place-de-l%E2%80%99ind%C3%A9pendance-la-ville-de-dakar-va-proc%C3%A9der-au-lifting.

Table 3.3.1. Geological formations and corresponding geotypes of Dakar.

Code	Geotype Name	Geological Formations
APA	Plains alluvium	Fz (clay, sand and pebbles) CF (argillaceous sand)
CE	Colluvium-eluvium	Ferrous duricrust
EOL	Dune sands	Red sands (Dv-y), white sands (Dlz4) et yellow dune sands (Dlz3)
GR	Sandstone	Shelly sandstone (My)
LF	Bottom lacustrine	Argillaceous (LgMz, Lgz) and loamy (Mz2-4) sands
LS	Littoral sands	Shelly (Sgz), beach (Mz2-4) and littoral sands
P	Palustrine deposits	Humus-bearing sands (FTz, Tz)
R	Infill	
CA	Argillaceous limestone	Argillaceous limestone and marlstone-limestone
LAV	Lava	Streams of hawaiite (d5ß, m5ß, scn5ß) and basanite (4ß, 3ß)
M	Marl	Clays et marl (e4a, e2b, e1-3a)
	MC – Alternating marl and limestones	Alternating marlstone-limestones (e5b, e5c, e4b5, e4b1-4) Shelly limestone and marls (e1)
PYR	Pyroclastic rocks	Volcanic tuff (5tf, scr5tf, 3tf, 2tf)

traces of volcanic activity are found on the Yoff Plateau, near the remains of two volcanic columns (known locally as *Les Mamelles*), with remains from Pleistocene lava flows (geotype LAV) alternating with pyroclastic rocks generated by volcanic explosions (geotype PYR).

Apart from shallow utilities, several basements, subterranean canals and building foundations, Dakar's underground construction is limited. This cannot, however, be attributed to poor geological conditions or the lack of knowledge about the characteristics of the geology. A lithological study carried out during the last update of the geological maps of Senegal in 2009 evaluated the geotechnical aptitude of the geological formations of the country.[17] The lavas (LAV) have a high suitability for deep building foundations. The littoral sands (LS), alternating limestone and marl (MC) and pyroclastic rocks (PYR) are appropriate for surface foundations and are able to support heavier constructions. The marl and clay (M) formations as well as the dune sands (EOL) are only appropriate for the surface foundations of lighter buildings (individual residences, etc.) or heavier buildings where foundations are built deeper for structural reasons. According to a local hydrogeologist, the yellow dune sands are used for concrete aggregate and the reddish sands are used for the construction of non-load-bearing bricks. The palustrine deposits (P), however, have little to no construction potential, due to their high saturation of water and high compressibility leading to local subsidence.

[17] Barusseau et al., "Notice explicative de la cartographie multi-couches à 1/50000 et 1/20000 de la zone d'activité Cap-Vert."

The potential of the geotypes to contain groundwater is the combination of both their known water content and their permeability. The two main aquifer systems of the Cap Vert peninsula are found in the quaternary formations, with the infrabasaltic aquifer located in ancient dune sands (EOL) confined beneath volcanic tuff (LAV) and pyroclastic rock (PYR). Where the aquifer system is no longer confined, it feeds into the quaternary sands aquifer situated in the dune (EOL) and littoral sands (LS) on the isthmus. The plains alluvium (APA) also has a high permeability that is suitable for the movement of groundwater. The substratum beneath is constituted by an impermeable lay of clay and marl (M), which is the lower barrier of the aquifer systems of Dakar. The layer of alternations of limestone and marl, because of the limestone, is somewhat permeable and could contain part of the deeper portions of the quaternary sands aquifer. A report by the DGPRE finds that there is some of the quaternary sands and infrabasaltic aquifers that infiltrates slowly into the marl substratum.[18]

Geothermal energy is not one that is currently widely used in Senegal. A report commissioned by the Ministry of Energy in 2011 rated the potential for this alternative renewable source of energy as low, because of the lack of a high geothermal gradient and the availability of other, more easily exploitable, renewable energies.[19] Local geologists gave a similar response when asked about Dakar's potential use of geothermal, citing the low geothermal coefficient (meaning the low rate of temperature increase by depth). This is unfortunate given that geothermal energy is not only based upon the temperature of the ground, but also its thermal conductivity. While temperature plays an important role, the presence of groundwater increases the possibility for heat to be extracted from—or sent from the surface into—the ground. The composition of the geology is also important. Certain geological formations have a higher conductivity than others. Furthermore, the rate of flow in the aquifer carries additional energy that can also be extracted. While those types of systems are not often placed in aquifer systems used for drinking water, when the groundwater is not potable, geothermal can be an alternative energy source.[20]

3.3.2.1. Geology at Various Depths

The geological section of the western portion of Cap-Vert, stretching from the northern coast near Yoff down to Cap Manuel (presented at the beginning of the chapter), reveals the principal geological layers of the peninsula (Figure 3.3.2, above).[21] At the surface around

[18] Direction de la gestion et de la planification des ressources en eau (DGPRE), "Note sur la synthèse des études hydrogéologiques sur les ressources en eau souterraine exploitées pour l'AEP de Dakar et de la Petite Cote," Note (Dakar: Ministère de l'Hydraulique et de l'Assainissement, 2010).

[19] Claudia Hrubesch, "Les énergies renouvelables. Les bases, la technologie et le potentiel au Sénégal" (PERACOD, 2011).

[20] Aurèle Parriaux, *Géologie: bases pour l'ingénieur* (Lausanne, Suisse: Presses polytechniques et universitaires romandes, 2009).

[21] Crevola, Cantagrel, and Moreau, "Le volcanisme cénozoïqe de la presqu'île du Cap-Vert (Sénégal): cadre chronologique et géodynamique."

the former volcano (*les Mamelles*) is a layer of volcanic rock and lava formations. The layer of sand in which the infrabasaltic sands are contained clearly decreases in thickness towards the south. This limit point, as previously mentioned and illustrated here, is constituted by the argillaceous layer, which outcrops on around Medina (*l'Anse des Madeleines* in the section) and towards Cap Manuel. Further towards the isthmus, the sands are no longer confined and combine with littoral sands.[22]

The presence of the geotypes and therefore the geological qualities and resource potentials change by depth. As shown in Figure 3.3.2, the first 15 meters are characterized by three difference zones: a zone around Medina, Cap Manuel and the Plateau around the port with a layer of dune sands (EOL) over marl (M); the part of the plateau where the volcanic formations (LAV/PYR), alluvium (APA) and dune sands (EOL) overlay the (infrabasaltic) sand and marl (M); and the isthmus, where dune sands (EOL) and palustrine deposits (P) overlay alternating marl and limestones (MC). At 15-30 meters deep, the isthmus is mostly dune sands, with some marl deeper down towards the inland, the remainder of volcanic layers and some alluvium over dune sands and some marl on southern portion of the Cap. From 30-45 meters deep, the morphology of the argillaceous substratum is evident as the amount of marl is gradually replaced by dune sands towards the north. The high elevation of the former volcano (*Les Mamelles*) means that even at 45 meters from the surface, volcanic formations are still present

The location of the geotypes at these three depths is of course an approximation, but was based on the map of the top of the argillaceous layer[23], the thickness of the infrabasaltic aquifer and height of the groundwater provided in map form and as raw digitized borehole data from the DGPRE[24], and the topographical data included with the geodatabase acquired from the ANAT (*l'Agence nationale de l'aménagement du territoire*). Table 3.3.2 summarizes the format, source and main transformations performed upon the data used in this study.

3.3.2.2. Resource potentials by layer

The calculation of potential for the geotype layers conducted the Analytic Hierarchy Process differently than for San Antonio and Hong Kong. Dakar has both a larger number of geotypes than San Antonio. Unlike San Antonio, the pairwise comparison process involved local experts who were recruited on the two-week visit in March 2016. In order to make better use of the experts' time, a clustering technique was adapted from one proposed by researchers developing the AHP.[25] This technique involved first asking the

[22] Barusseau et al., "Notice explicative de la cartographie multi-couches à 1/50000 et 1/20000 de la zone d'activité Cap-Vert."

[23] Ibid.

[24] GKW Consulting, "Projet Eau à Long Terme — Études hydrogéologiques complémentaires," Intervention report (Dakar: Ministère de l'Agriculture, de l'Élevage et de l'Hydraulique, 2004).

[25] Thomas L. Saaty and Luis Gonzalez Vargas, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*, 2. ed, International Series in Operations Research & Management Science 175 (New York: Springer, 2012).

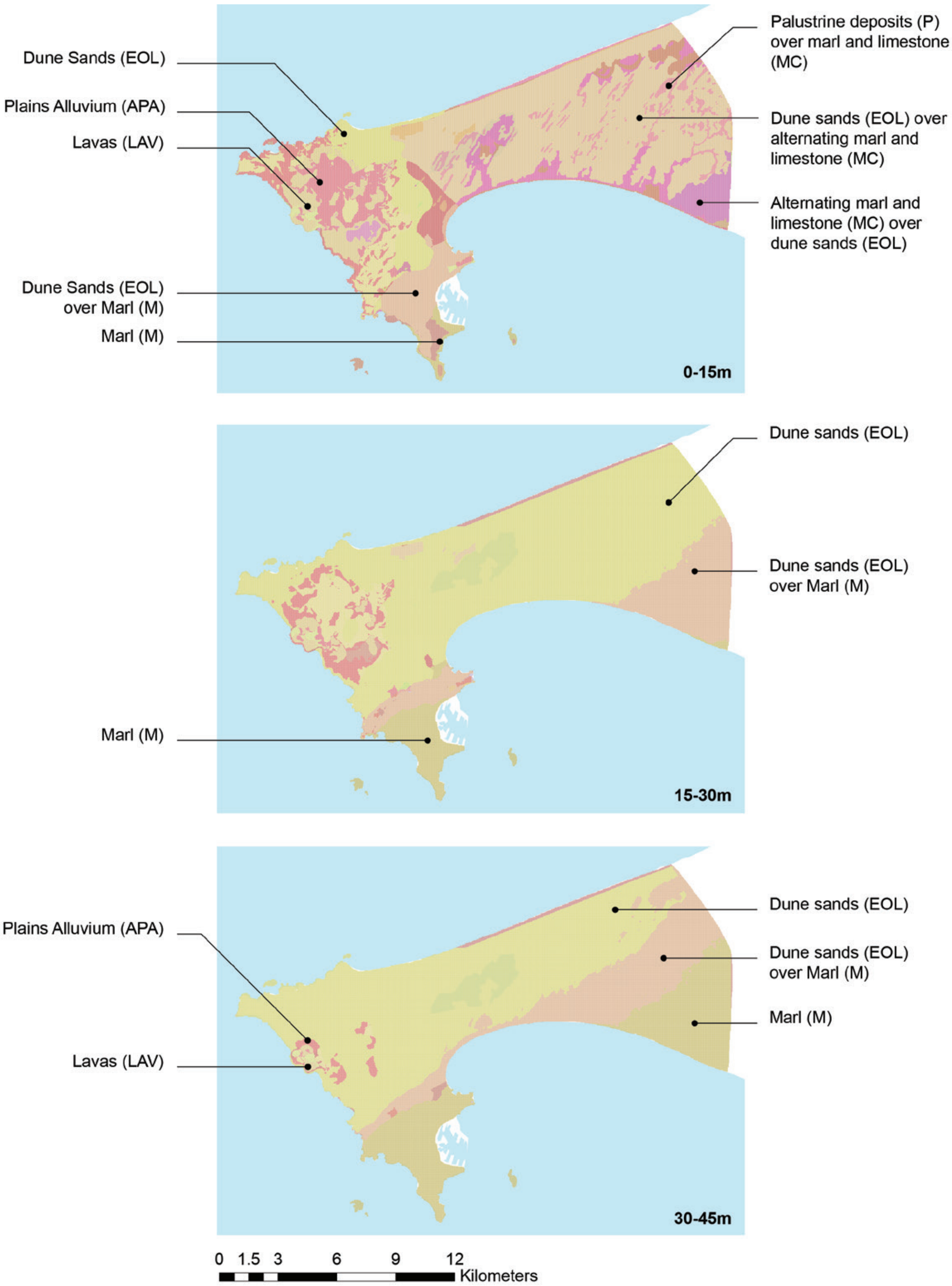


Figure 3.3.3. The approximate location of geotypes at 0-15 meters, 15-30 meters and 30-45 meters below the surface.

Data Source(s)	Format	Initial Transformations
Geological Superficial and Subsurface Maps 1:20k and 1:50k(DMG)	TIFF	Project and render vectorial in ArcGIS
Elevation of terrain (ANAT)	Polyline SHP	Into raster database
Top of argillaceous layer (DGPRE)	Polyline SHP / JPEG	Extend polyline from infrabasaltic zone to cover the peninsula, referring to an additional map from the DGPRE PELT
Thickness of Infrabasaltic sands (DGPRE)	Polyline SHP	None
Groundwater Level (DGPRE)	Point SHP (n=2931)	Interpolation using Kriging and 3 points of the static level of the aquifer recorded in borehole data.
Building Footprints (ANAT)	Polygon SHP (with Z values)	Calculation of Built Volume using the elevation of terrain to estimate building height.
Street Centerlines (OSM)	Polyline SHP	Topological verification and removal of orphan road segments.

SHP = ESRI shapefile or equivalent; ANAT = *Agence nationale de l'aménagement du territoire*; DGPRE = *Direction de la gestion et de la planification des ressources en eau*; DMG = *Direction des mines et de la géologie*; PELT = *Projet eau à long terme*; OSM = OpenStreetMap

Table 3.3.2. Format, source and main transformations of data used in the calculation of potential.

experts in Dakar to score the overall potential of each geotype for the four resources, which placed the geotypes in three to four groups and then carrying out pairwise comparisons within the groups. Responses were gathered using surveys composed in Typeform for the web (Appendix 3.3.1).[26] The suitability vector is then constructed by linking each comparison sub-matrix by the element of highest suitability of one matrix to the lowest of the next. The application of this method will be demonstrated below.

The survey for the first phase contained 40 questions, one for each of the ten geotypes for four different resources. One geotype was eliminated to make the survey shorter, lacustrine bottom sediments (LF), of which there are so few in the study area that it was not worth including. The survey allowed the respondent to skip a resource for which he did not feel qualified. Nine experts were contacted and two, a professor of geomorphology and a hydrogeologist, responded (see Appendix 3.3.1). For comparison, the author's geologist co-advisor also participated. The survey took anywhere from 15 to 25 minutes to respond. The geomorphologist did not respond to questions on the geothermal potential of the geotypes and the hydrogeologist skipped the questions concerning the geomaterial suitability. Where the answers of the experts was surprising or confusing, the experts were contacted on an individual basis to better understand their reasoning. Responses to the geothermal potential were so low (due, according to the hydrogeologist, to a low geothermal potential in Dakar), that it was decided to rely on only the conductivity of the geotypes themselves, rather than to rely on expert opinion in a city where there is little practical experience with geothermal energy.

The exercise produced four groups for constructability, geomaterial suitability and groundwater potential (Figure 3.3.3). The appreciation of the geothermal potential was based on the

[26] www.typeform.com

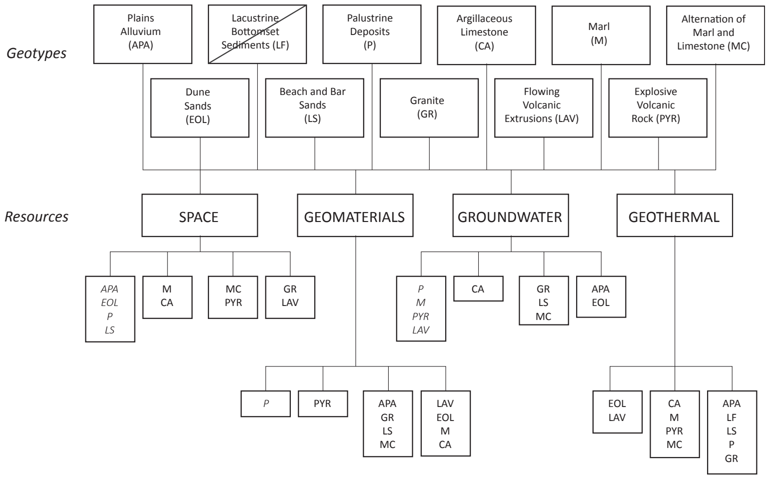


Figure 3.3.4. Geotype Grouping in First Phase of Pairwise Comparison Consultation.

thermal conductivity of the formations and produced three groups. This grouping matches well with the information provided in the notes accompanying the geological maps. The lava (LAV) and sandstone (GR) formations have a higher geotechnical aptitude than the alternating marl and limestone (MC) formations and pyroclastic rocks (PYR). However, the pyroclastic rocks (PYR) have a significantly lower suitability for use as geomaterials than the lavas (LAV). Groundwater potential is logically highest in the quaternary formations (APA, EOL, LS), with the alluvium (APA) and dune sands (EOL) judged as having a greater potential than the littoral sands (LS). The geothermal grouping could not be compared with empirical information on Dakar, but most of the geotypes having a higher thermal conductivity are situated on the Yoff Plateau. The conductivity of the formations also depends on the local groundwater saturation and their content in iron. According to a local geomorphologist from the University of Dakar, the red sands (part of the EOL geotype) would have a slightly higher potential where the amount of iron is higher.

The first phase identified the geotypes to be compared pairwise, meaning those placed in the same group. For constructability, this meant three comparisons, with twelve for geomaterial suitability and four for groundwater (Figure 3.3.4). The 19 questions were again addressed to the nine experts, with responses from the same professor of geomorphology and a professor of geology who did not participate in the first phase. The survey was constructed following the same logic as in Hong Kong, with an initial question asking which of the two alternatives (for Dakar, it was the geotypes) was more suitable than the other followed by the opportunity to provide a rating from 1 to 9 of how much more suitable one was for the other. Follow-up questions were sent to the experts when their evaluations diverged by more than three points.

For composing the comparison matrices, each group was placed in a single matrix. The group with the lowest rating was not included, because it contained the geotypes for which potential was zero. However, in the clustering process, the highest geotype of the next lowest group needed to be included in the comparison in order to establish a proportional relationship between each comparison sub-matrix.[27] The pairwise comparison scores were weighted according to the number of comparisons made in comparison to the total number. For the space potential of each geotype, for instance, the first group (APA, EOL, P and LS) was considered of lowest interest so no comparison was made between them. Rather, one was chosen at random to be placed in the same matrix as the marl (M) and limestone (CA) geotypes (Table 3.3.3.). It was given a score equivalent to the lowest suitability, so normally 9 in relationship to CA and M, but this was actually 3 when considering that the table was making 3 of a total of 9 comparisons so the max score was reduced by being multiplied by 1/3. Similarly, the experts evaluated limestone (CA) as more suitable to marl (M) with a score of 6, which when weighted becomes 2.00 as shown in Table 3.3.4.

The second table (3.3.4) followed the same logic, this time including the highest scoring geotype from the previous table, in this case limestone (CA). The suitability vector was calculated in the same manner and then weighted to account for its relationship to the suitability vector of group 1. The scores of the limestone geotype from each table establish the proportion used to adjust the vector of group 2. For the alternating marl and limestone geotype (MC), this means dividing by the CA score in group 2 (0.142) and multiplying the result by the CA score in group 1 (0.525), giving the adjusted value of 1.32. The third group (3.3.5) was calculated in the same fashion. This clustering process was carried out for each of the four resource potentials and produced four adjusted suitability vectors, which were normalized to remain between 0 and 1 (Table 3.3.6). The highest constructability potential is found among the lava (LAV), sandstone (GR) and pyroclastic (PYR) geotypes. The lava geotype is also most suitable for geomaterial reuse, followed by dune sands (EOL) and the limestone (CA). The dune sands (EOL) also scored the highest along with the plains alluvium (APA) for groundwater potential. The lava formations (LAV) were also deemed to have the highest relative geothermal potential. Each of these potentials depends of course on other factors, which will be presented in more detail after examining the spatial distribution of the geotypes and their resource potentials.

The potential for buildable space tends to be higher in the volcanic foundations (LAV/PYR) of the Yoff Plateau as well as on the isthmus where the marl (M) and alternating marl and limestone (MC) (Figure 3.3.5). This is due to the general stability of these formations for foundations. The argillaceous quality of the marl, however, can pose a problem where major changes in water content leads to expansion or contraction. The diagnostic of the Horizon 2025 master plan highlighted this problem of differential settlement

27 Ibid.

	CA	M	APA	Suitability Vector
Limestone (CA)	1.00	2.00	3.00	**0.525**
Marl (M)	0.50	1.00	3.00	**0.334**
Alluvium (APA)	0.33	0.33	1.00	**0.142**

Consistency index of 0.03 (tolerable limit of 0.10)

Table 3.3.3. Comparison matrix for buildable space potential group 1.

	PYR	MC	CA	Suitability Vector	Adjusted Value
PYR	1.00	1.67	3.00	0.500	**1.85**
MC	0.50	1.00	3.00	0.357	**1.32**
CA	0.33	0.33	1.00	0.142	

Consistency index of 0.01 (tolerable limit of 0.10)

Table 3.3.4. Comparison matrix for buildable space potential group 2.

	LAV	GR	PYR	Suitability Vector	Adjusted Value
LAV	1.00	2.67	3.00	0.560	**7.37**
GY	0.50	1.00	3.00	0.299	**3.94**
PYR	0.33	0.33	1.00	0.140	

Consistency index of 0.05 (tolerable limit of 0.10)

Table 3.3.5. Comparison matrix for buildable space potential group 3.

Geotype	Constructability / Space	Geomaterials	Groundwater	Geothermal
APA	0.009	0.029	0.269	0.020
EOL	0.009	0.235	0.504	0.000
LS	0.009	0.047	0.126	0.027
P	0.009	0.000	0.000	0.009
GR	0.254	0.020	0.058	0.118
CA	0.034	0.144	0.011	0.120
LAV	0.476	0.405	0.000	0.416
M	0.022	0.102	0.000	0.077
PYR	0.119	0.006	0.000	0.075
MC	0.085	0.013	0.032	0.139

Table 3.3.6. Normalized (0-1) adjusted suitability vectors for four resources and 10 geotypes.

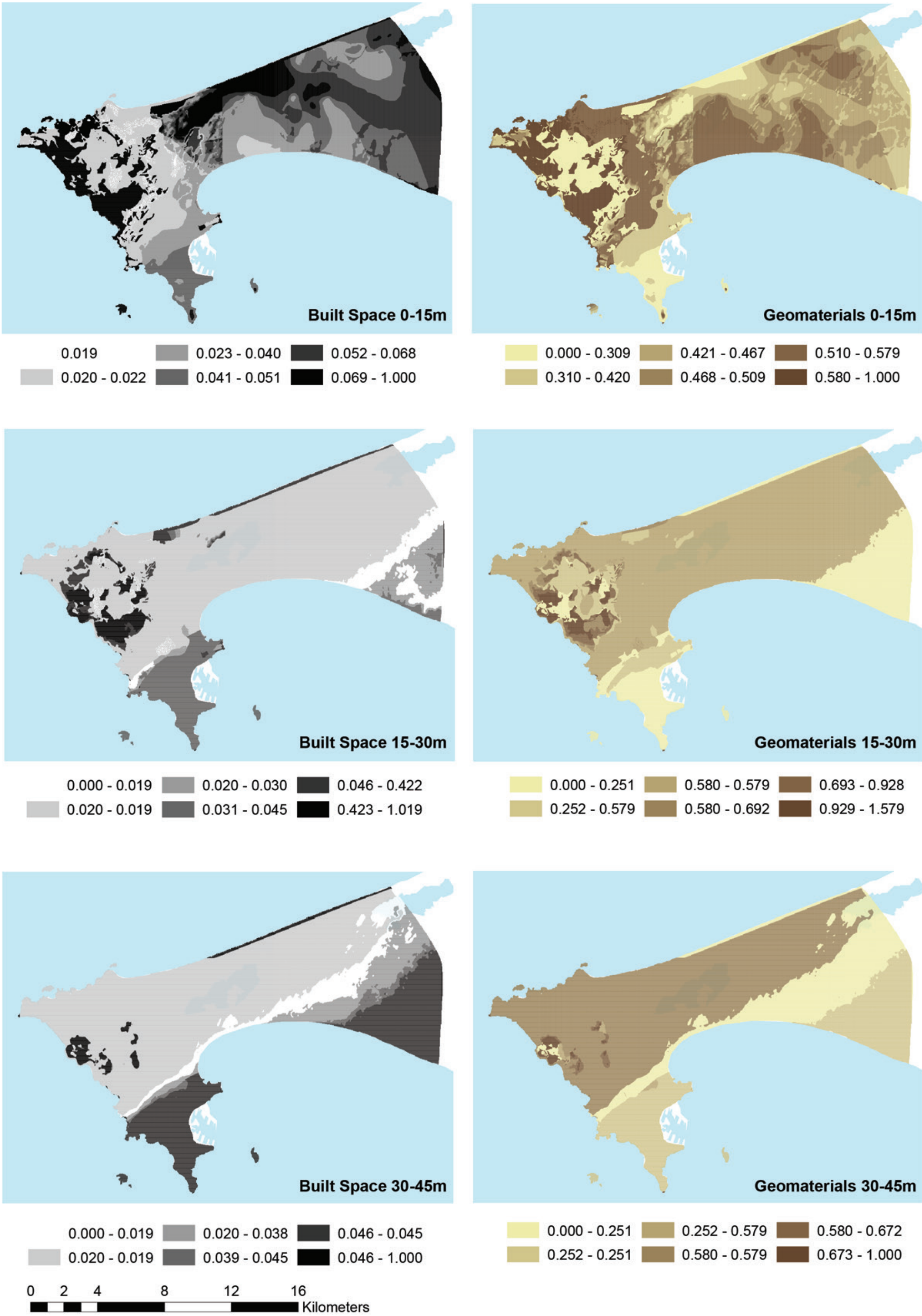


Figure 3.3.5. The distribution at three depths of the constructability for underground space and use of geo-materials.

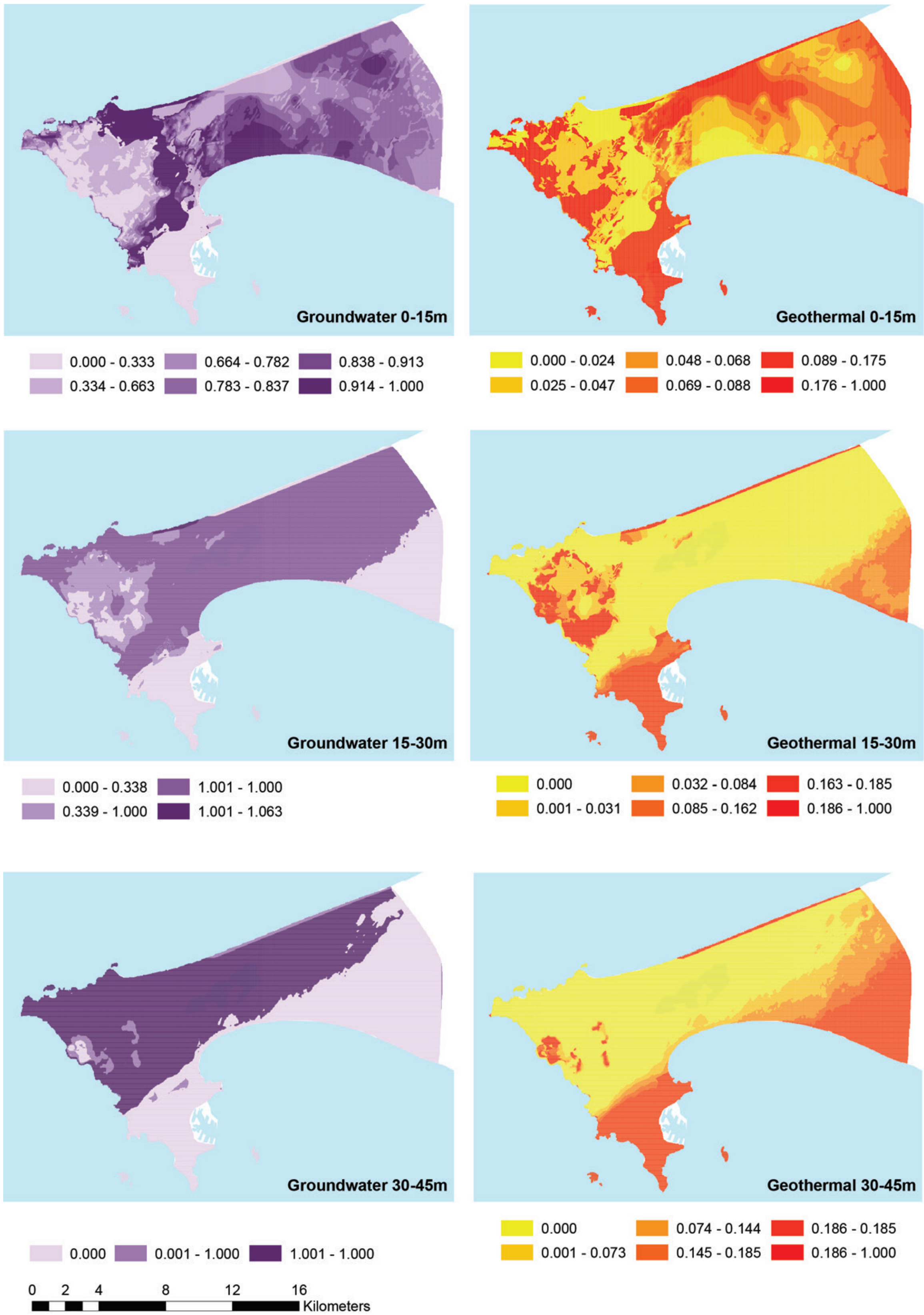


Figure 3.3.6. The distribution at three depths of the potential for groundwater and the thermal conductivity for geothermal energy.

in several communes on the isthmus.[28] Deeper beneath the surface (15-30m), the potential is more homogeneous, containing for the most part the remnants of dune sands. The marl that constitutes the substrate begins to appear in the southern parts of the Cap and towards Rufisque, but is fully present at 30 to 45 meters deep. Except in the volcanic formations (LAV), the geomaterial potential does not overlap with the potential for built space. The dune sands (EOL) can be good geomaterials, but do not provide foundational stability. The marl can provide good foundational support in the right conditions, but is not as suitable as a geomaterial. This suggests that extraction of space for the marl will have to deal with the disposable of sands found on the surface that may not be of immediate value. This will depend as well on continuing research conducted on the treatment of these sands for construction materials or other uses.

The distribution of groundwater potential at different depths reflects the permeability of the geological formations, particular the sand (EOL/LS) and alluvium (APA) geotypes. The maps in Figure 3.3.6 only rely on the permeability of the formations and not on the actual presence of water, which will have to be captured with other data. The sands are considered to be of good permeability which is why potential remains high where the sand is still present. 30 to 40 meters deep, the marl begins to dominate from its closer proximity to the surface and the potential gradually decreases. The impermeable formations on the Yoff Plateau are characterized by a lower potential. The representation of geothermal potential follows closely that of the potential constructability for underground space, with a lower potential where there is less marl and more sand and a higher potential in the volcanic formations. The geothermal evaluation is based upon the thermal conductivity of the geotypes in their saturated state. Where there is less water, the conductivity may be lower.

3.3.3. Urban potential: pervasive centrality using PCA.

Similar to the case studies of San Antonio and Hong Kong, the measure of underground space potential is improved by a spatial network analysis of the surface urban morphology. In each case, the type of evaluation depends on the characteristics of the data used to represent the movement network of the city. For San Antonio, the parcel data included total built surface area and land use. In Hong Kong, census data was placed on the street segments as population densities of the street block and territorial planning units. In Dakar, the building footprints from 2013 were calculated from Lidar data, from which it was possible to calculate built volume and use it to weight the analysis at the building scale. Land uses, residential and employment data were not available for Dakar in a format that would make it possible to accurately identify the activities found at each address. In a city where so much of the economy, from residential

[28] Cities Alliance Project, "Stratégie de développement urbain du Grand Dakar (Horizon 2025)."

status to employment, is conducted informally or haphazardly, the accuracy of such data would be questionable.[29]

The network dataset was built in ArcGIS 10.3 using the street centerline data downloaded freely from OpenStreetMap, which turned out to be more complete than the centerlines included in the Dakar geodatabase, particularly in residential and 'informal' areas. To focus on pedestrian movement, the highway was eliminated from the network as a place where pedestrians could walk legally. Each block of buildings was converted to a point located along the nearest street segment. Buildings that were clearly dependencies or sheds were eliminated (about 18 m^2 or less). The spatial analysis conducted using the UNA Toolbox v.1.1 and the gravity, betweenness, turns and straightness metrics were run at several radii from 100 to 3200 meters. Unlike the evaluations of spatial potential of San Antonio and Hong Kong, a particular radius was not chosen, but rather, similar to what was done analytically with Montreal, the measures were placed in a principal component analysis and reduced to a series of vectors representing categories of spatial connectivity (or of pervasive centrality[30]) to which each building has a degree of membership.

Before discussing the urban potential as access to built volume, it is interesting to examine the distribution of this volume over Cap-Vert (Figure 3.3.7). The highest built volumes are concentrated on the Plateau around the commercial district (surrounding the Place de l'Indépendance, in particular), the center of historic Medina, the industrial sector following the rail line inland along the southern coast, Grand Dakar, parts of Grand Yoff and the Parcelles Assainies. In general, built volumes gradually decrease towards the isthmus. The centrality analysis was interested in the connectivity of each of these buildings to all other buildings at a particular radius, weighted by the built volume. A principal component analysis was conducted on the resulting 24 measures. The turns metrics were removed because they told a different spatial story than the other metrics. The betweenness measures at 100, 200 and 3200 as well as the straightness measure at 100 and 3200 were also removed as they were particularly unique.[31] Of the three components produced, the first principal component, 'pervasive global centrality' captured the distributions of gravity and straightness metrics from 400 to 3200 meters and the second, 'pervasive local centrality', picking up the distribution of these two metrics from 100-, 200- and 400-meter radii. The third component, 'pervasive path centrality', captured the betweenness metrics from radii of 400 to 1600 meters (Figure 3.3.8).

[29] Chenal, "Urbanisation, Planification Urbaine et Modèles de Ville En Afrique de l'Ouest: Jeux et Enjeux de L'espace Public."

[30] Bill Hillier, "Spatial Sustainability in Cities: Organic Patterns and Sustainable Forms," in *Proceedings of the Seventh International Space Syntax Symposium*, ed. D. Koch, L. Marcus, and J. Steen (Stockholm: Royal Institute or Technology, 2009), K01.1-K01.20.

[31] It is admittedly not ideal to remove any metrics and this constitutes some of the limits of PCA. Future work may either need to explore alternative dimension reduction methods (like self-organizing maps) or account for the removed metrics in a different way.

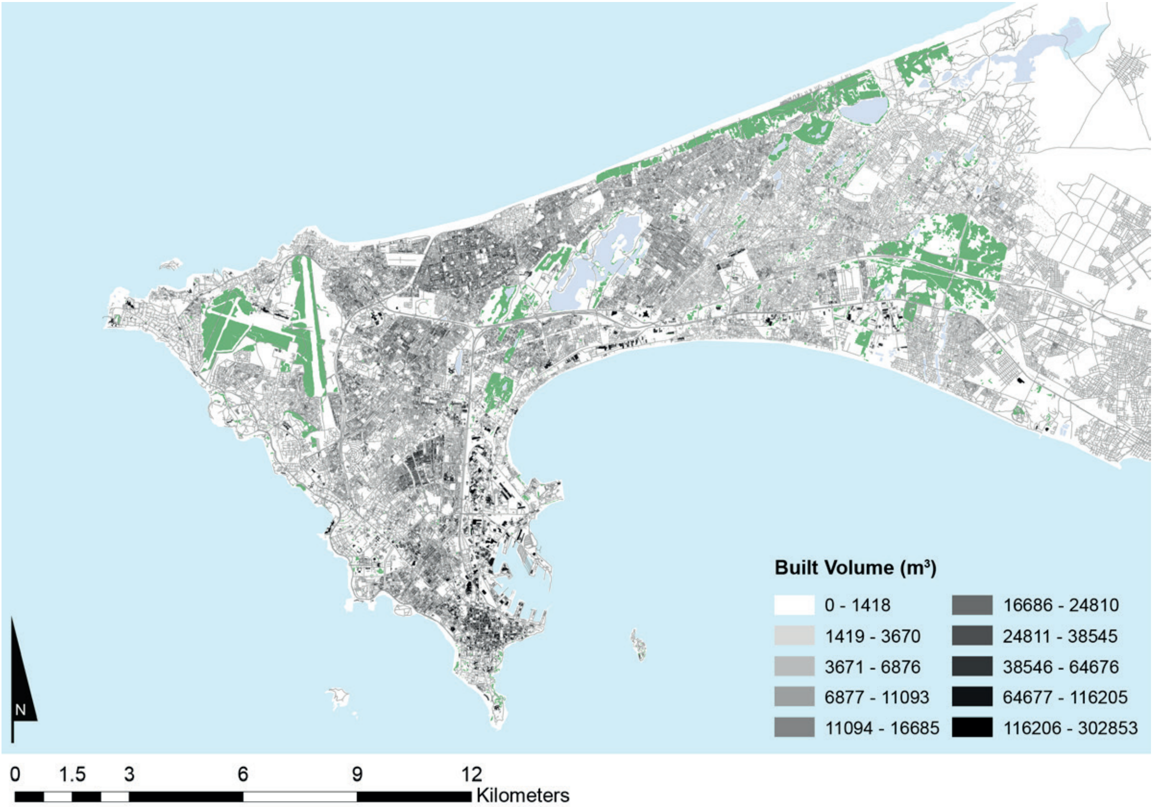


Figure 3.3.7. The distribution of built volume over Cap-Vert.

Built volume viewed from the point of accessibility along paths in the movement network reveals more about the logics of encounter and avoidance of the urban form than through a geographic distribution of only built volume. The areas of the town that are characterized the strongest by the pervasive global centrality component are situated in a series of clusters that follow the main roads up the center of the Cap (Figure 3.3.9), from Dakar-Plateau, Medina, Grand Dakar, Grand Yoff to the Parcelles Assainies and eventually to Pikine Nord and Pikine Est. The industrial area is clearly (and logically) disconnected from this movement network, excluding an area around Hann at the start of the isthmus. The part of the urban tissue on the Yoff plateau to the west of the airport is less central as larger radii. Several local centers emerge by mapping the pervasive local centrality component: a portion of the industrial zone, Ouakam north of *Les Mammelles* and south west of the airport, Ouest Foire east of the airport, Dalal Jamm east of the Parcelles Assainies and Mbao out to the east towards Rufisque. If these locations are worth highlighting, it is because they are either identified as or near centers of future development interest for the Horizon 2035 master plan. The pervasive path centrality highlights the axes that are situated on the highest number of shortest paths between buildings (weighted by built volume). These corridors include the historic centers of Ouakam, Cambérène, as street traversing Yeumbeul and Thiaroye in the region of the *niayes* and a sector of Keur Massar. This form of path centrality is not considered by the Horizon 2035 plan, but

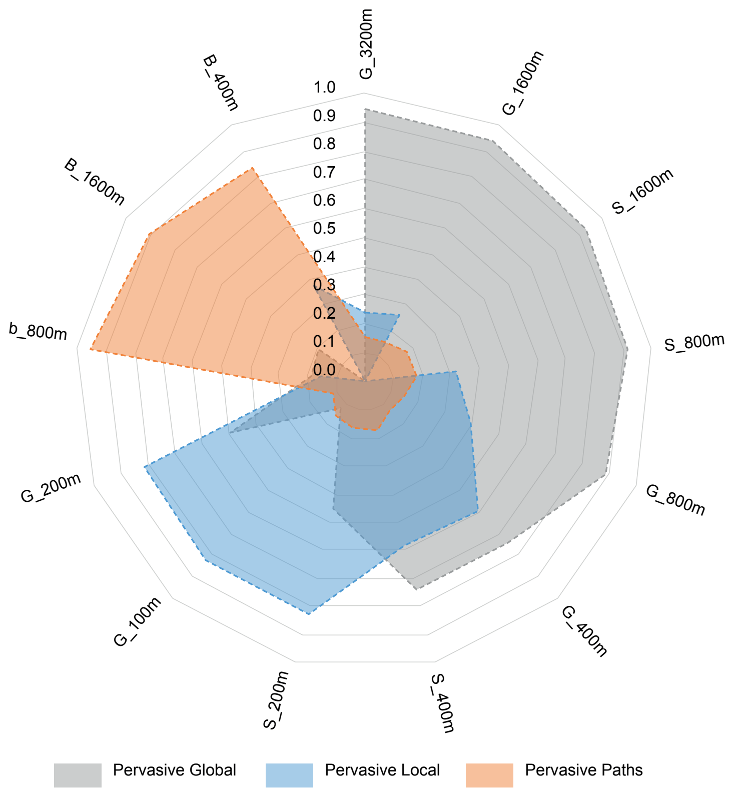


Figure 3.3.8. The principal component analysis revealed three categories of pervasive centrality, to which each building on Cap-Vert is given a value representing its degree of membership.

indicates places where commercial (or through-movement-seeking) activities would benefit from being located.

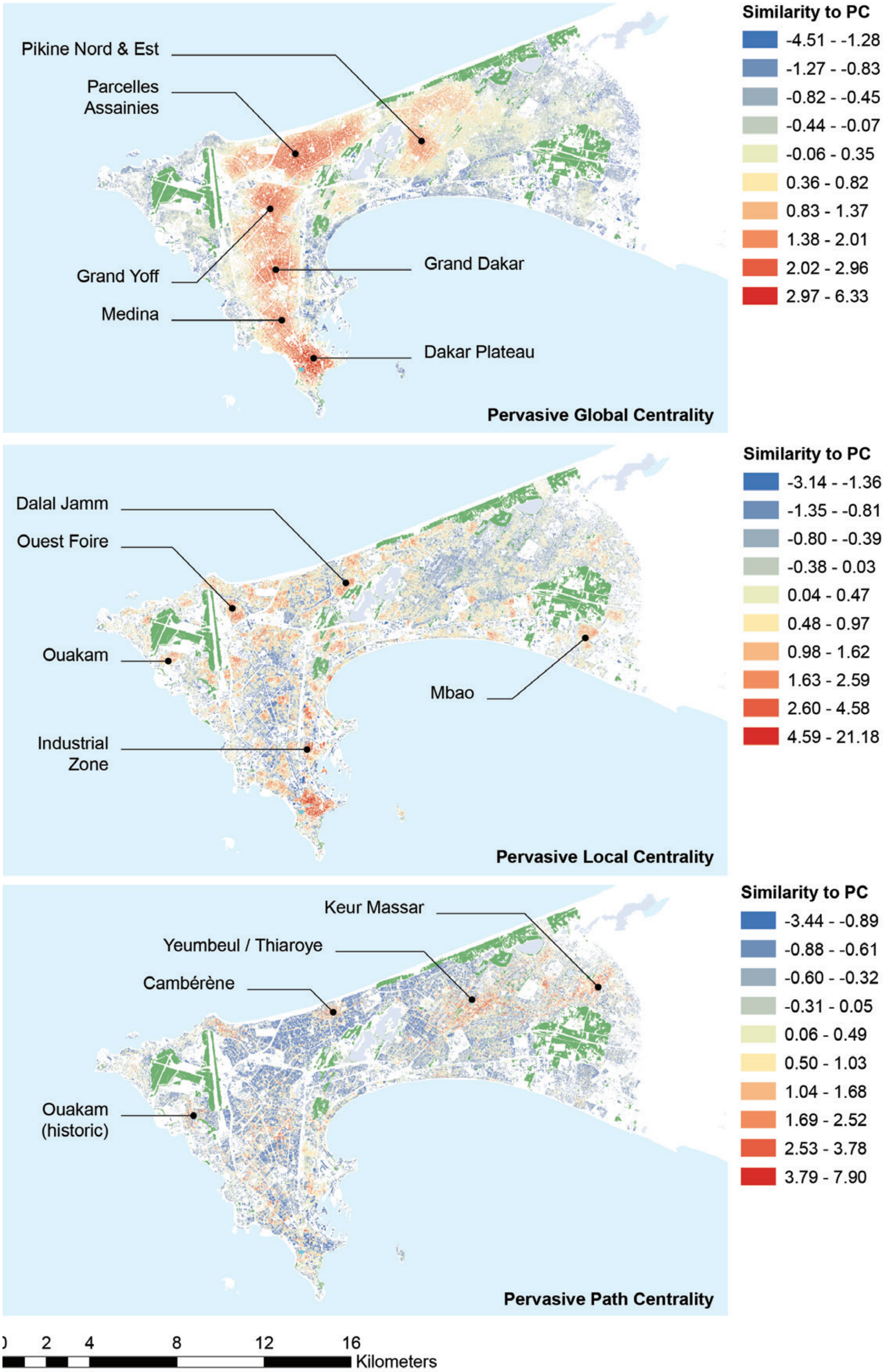


Figure 3.3.9. The distribution of the degree of membership as similarity to the principal component (PC), with red (positive) values indicating greater similarity and blue (negative) values indicating greater dissimilarity.

3.3.4. Results: Resource and Aggregate Underground Potentials

The volumetric potential of Dakar is not based solely on the nature of the geology and the centrality metrics. If geotype potential for constructability and urban centrality contributes positively to potential for underground space, the amount of groundwater (particularly if this is the infrabasaltic aquifer) and the elevation also play a role. Although technologically manageable, it requires greater energy and financial input to build in saturated ground, where the water infiltration will have to be prevented with a diaphragm wall or handled by regular pumping. In Dakar, the infrabasaltic aquifer, to a greater degree than the quaternary sands aquifer, is an important source of drinking water. The presence of the infrabasaltic aquifer therefore would decrease the potential for constructability. Outside the zone of the infrabasaltic aquifer, the limiting factor would be lower. The risk of flooding in Dakar varies by elevation, so being higher (above where previous flooding has been observed) is better.

Figure 3.3.10 illustrates the criteria for producing each resource potential. Urban centrality and elevation are only significant for underground space potential. Geomaterial potential, like space, takes the presence of groundwater as negative and therefore would be higher in areas with less groundwater, particular that of the infrabasaltic aquifer. Geothermal energy and groundwater potential are both positively affected by the height of the groundwater, but for geothermal, the infrabasaltic aquifer contributes to a slight decrease in potential, because of the risk that any geothermal system going into the aquifer inadvertently carries pollutants from the surface or from groundwater above. From the surface to the 45 meters below ground, the percentage of groundwater on the isthmus is greater than zero almost everywhere, except in some of the dune areas along the northern coast (Appendix 3.3.1). On the Cap, around the Yoff Plateau, there is no groundwater in the first 15 meters and only in certain areas is groundwater from 15 to 30 meters. However, by 45 meters below, there is groundwater and the ground is likely to be

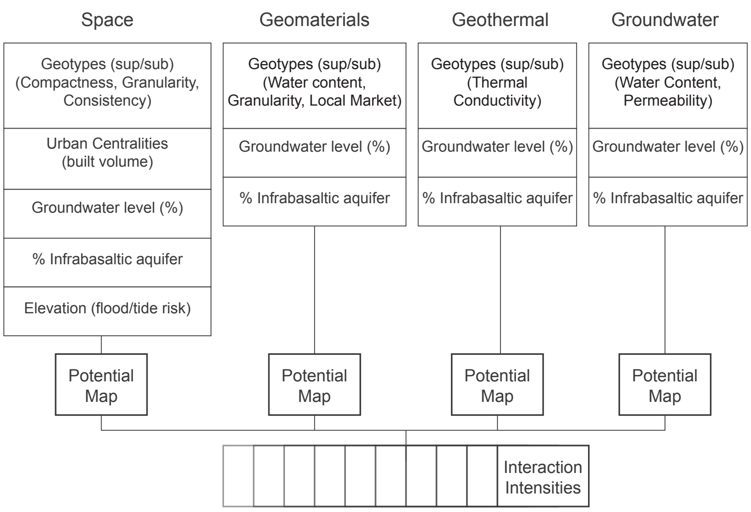


Figure 3.3.10. Selection of criteria to be aggregated in calculating the potential for each resource and then the overall resource potential and interaction maps.

saturated.[32] The depth and thickness of the infrabasaltic aquifer was modeled by GKW for the DGPRE and so the location of the aquifer can be identified with greater precision (Appendix 3.3.2). It follows the same pattern of the groundwater height and is complementary information. In some locations the groundwater height may actually correspond to that of the infrabasaltic aquifer, but it is possible that local groundwater (from rainfall) is found in the formations above the infrabasaltic. For this reason, the two sources of information are kept separate in calculating potential.

Certain criteria are absent from the evaluation of potential, either because the information was unavailable for all of Cap Vert or because it imposes artificial constraints. The presence of existing basements or underground canals for water evacuation is unknown. The drainage plan proposed by ADM recommends a network of tunnels throughout the isthmus.[33] These, however, are still in the preliminary phase and are only speculative at the time of writing. Also, existing planning proposals presented in the Horizon 2025 or 2035 masterplans are only preliminary recommendations and not indicative of a future state. It is in fact rare in Dakar's history that the master plan has been applied verbatim to the territory.[34]

As opposed to San Antonio, where weighting was done by the Deep City team, and Hong Kong where local collaborators at Arup and Associates did the comparisons, these criteria were left unweighted for Dakar. This means that the overall resource potentials are based solely on an aggregation of each normalized score for the risk-neutral order-weighted average calculation. The risk-averse and risk-taking aggregation procedures took into consideration only the criteria values themselves and did not incorporate any criteria weights.[35] This has the advantage of being less limiting in terms of the relative contributions of each criteria, however none of the criteria are by default more important than another.

3.3.5. Resource potential and interaction maps: from potential to potentiality

The maps of the four resource potentials tell slightly different stories about the distribution of potential over Cap-Vert (Figure 3.3.11). The potential for buildable space is higher on the Yoff Plateau and Cap Manuel, due to their elevation above sea-level, the presence of families of geological formations that are relatively stable for the construction of foundations and the lower groundwater table both over the infrabasaltic and quaternary sands aquifers. The area of higher space potential stretching along the northern portion of the isthmus from the Parcelles Assainies to Guédiawaye can

[32] The presence of groundwater, as mentioned previously, was interpolated from borehole data, which only indicates freely flowing water and not whether the ground is saturated (i.e. the ground is humid but a hole dug does not fill with water).

[33] Agence de développement municipal, "Plan directeur de drainage pluvial."

[34] Chenal, "Urbanisation, Planification Urbaine et Modèles de Ville En Afrique de l'Ouest: Jeux et Enjeux de L'espace Public."

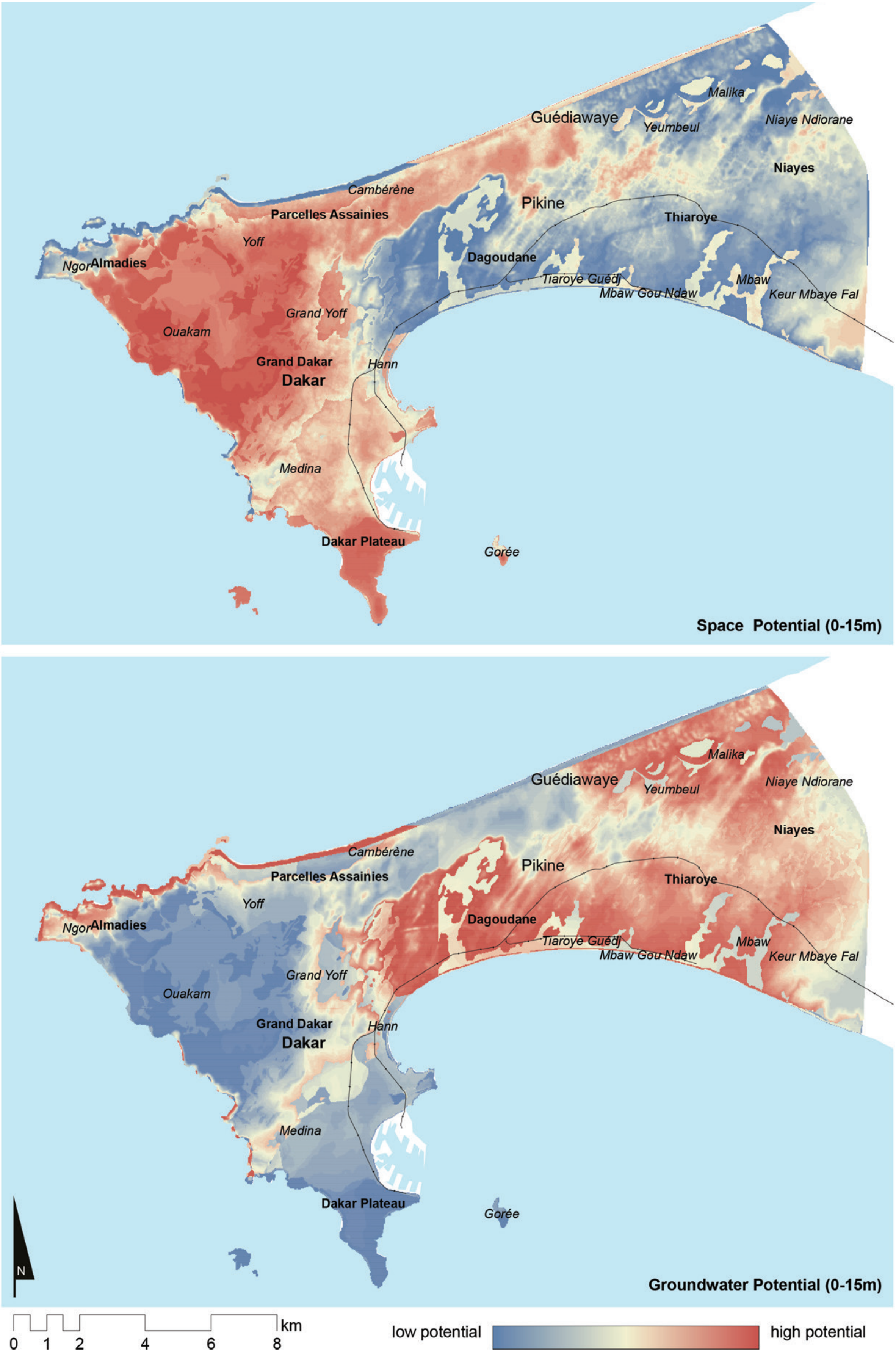
[35] An example of the python code for computing the space potential by depth is available in Appendix 3.3.3.

be explained by a higher elevation, leading to lower groundwater levels and a greater approximate thickness of the alternating marl and limestone (MC) geotype, which has a higher suitability for foundation construction than the dune (EOL) or littoral sands (LS) that cover much of the rest of the isthmus.

The distribution of geomaterial potential resembles, on a whole, that of the space potential, despite the potentials of the geotypes being quite different (as shown in Figure 3.3.5). This is probably due to the fact that the three criteria, two of which address the conditions of the groundwater, were given equal weight, therefore perhaps downplaying the importance of the geological conditions. However, particularly around Cap-Manuel, Medina and the Yoff Plateau, at first glance there appears to be a potential synergy between geomaterial and space potentials. This will be verified in the interactions maps below. There does not appear to be much synergy between the areas of groundwater potential, which are highest on the isthmus. This potential is as yet undetermined, meaning that it could be for drinking or for irrigation depending on the quality of the water. The level of the groundwater, the permeability of the sand geotypes clearly favors lower elevations than the higher ones along the plateaus and dunes to the north of the *niayes* region. The distribution of geothermal potential is less geographically contained and includes both areas of the Dakar and Yoff Plateaus and into the isthmus particular where the groundwater is high enough to ensure that the ground saturation affords a higher thermal conductivity. Some of these areas are even in the lakes themselves (for instance, west of Pikine), which may not be the best location for a geothermal system, but is indicative of certain favorable material conditions. Geothermal potential is lower where the infrabasaltic sands aquifer is present, which is why only zones comprised of geological formations (especially the lava geotype) with high conductivity show a high geothermal potential on the Yoff Plateau.

The combination of all four potentials in a single map reveals the zones of their overlap (Figure 3.3.11). The map resembles a combination of both the space and geomaterial maps, highlighting the areas on the cap where geothermal, geomaterial and buildable space potentials meet and the areas on the isthmus where geothermal and groundwater potentials are particularly high in the lowest lying areas. Because the maps are less about identifying the areas of highest potential, than of identifying areas of possible conflict and synergy, twelve interactions maps were created of all the possible combinations, including those where single resource potentials dominate.[36] Figure 3.3.12 presents these interaction potentials, with a score for each 25x25 grid location given according its similarity to a particular interaction type. The areas where interactions between all four resource potentials are present (a) extend from the around

[36] As opposed to the San Antonio case study where this strategy was first tested, the geomaterial and space potentials were kept separate.


Malika
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Yeumbeul
Niaye Ndiorane
Niayes
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Pikine
Parcelles Assainies
Thiaroye
Yoff
Dagoudane
Ngor
Almadies
Tiaroye Guédj
Mbaw
Mbaw Gou Ndaw
Keur Mbaye Fal
Grand Yoff
Ouakam
Grand Dakar
Hann
Dakar
Medina
Dakar Plateau
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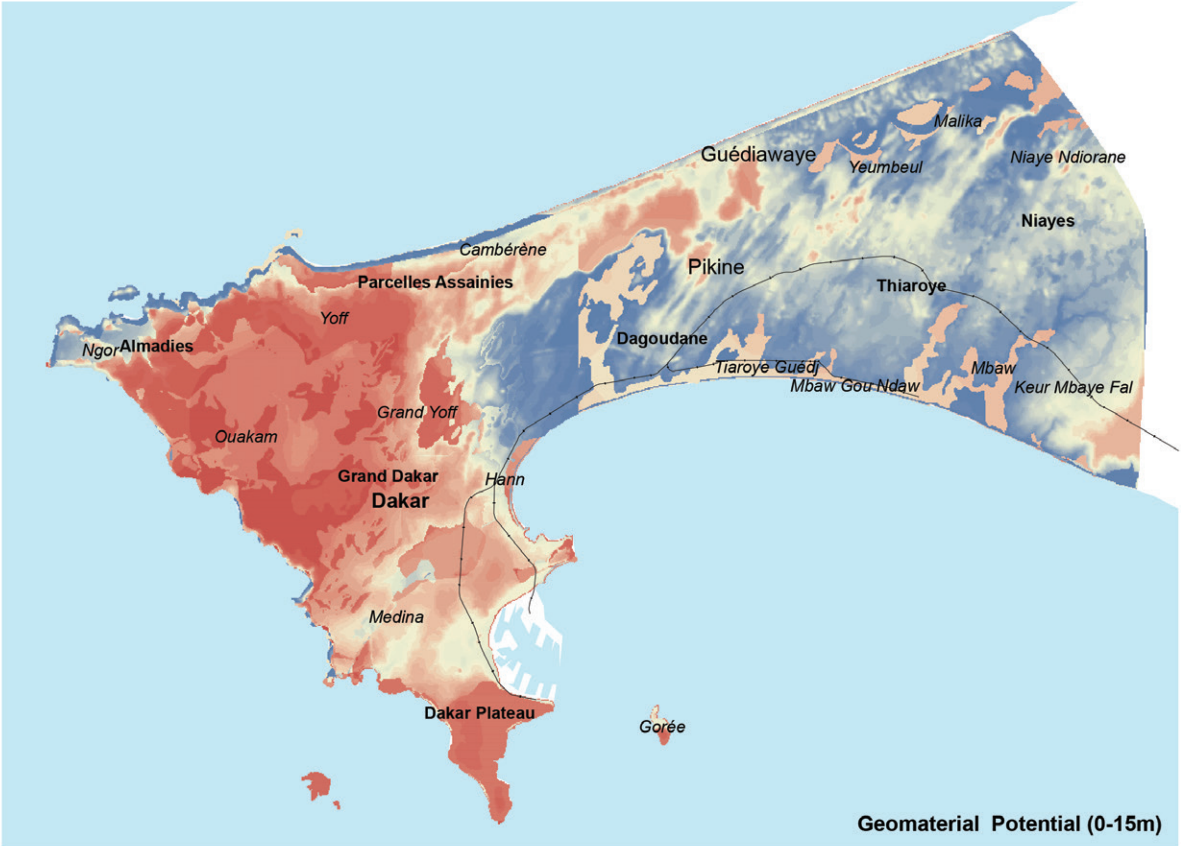
high potential



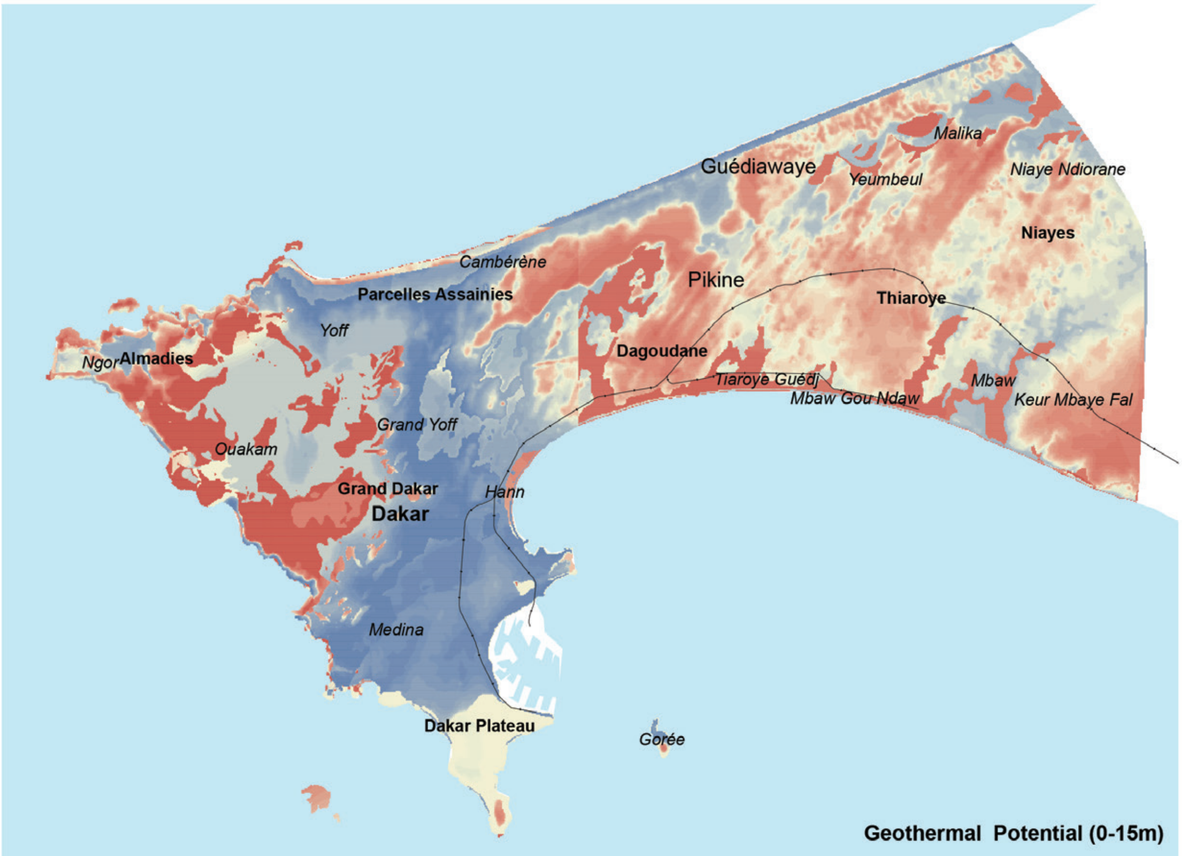
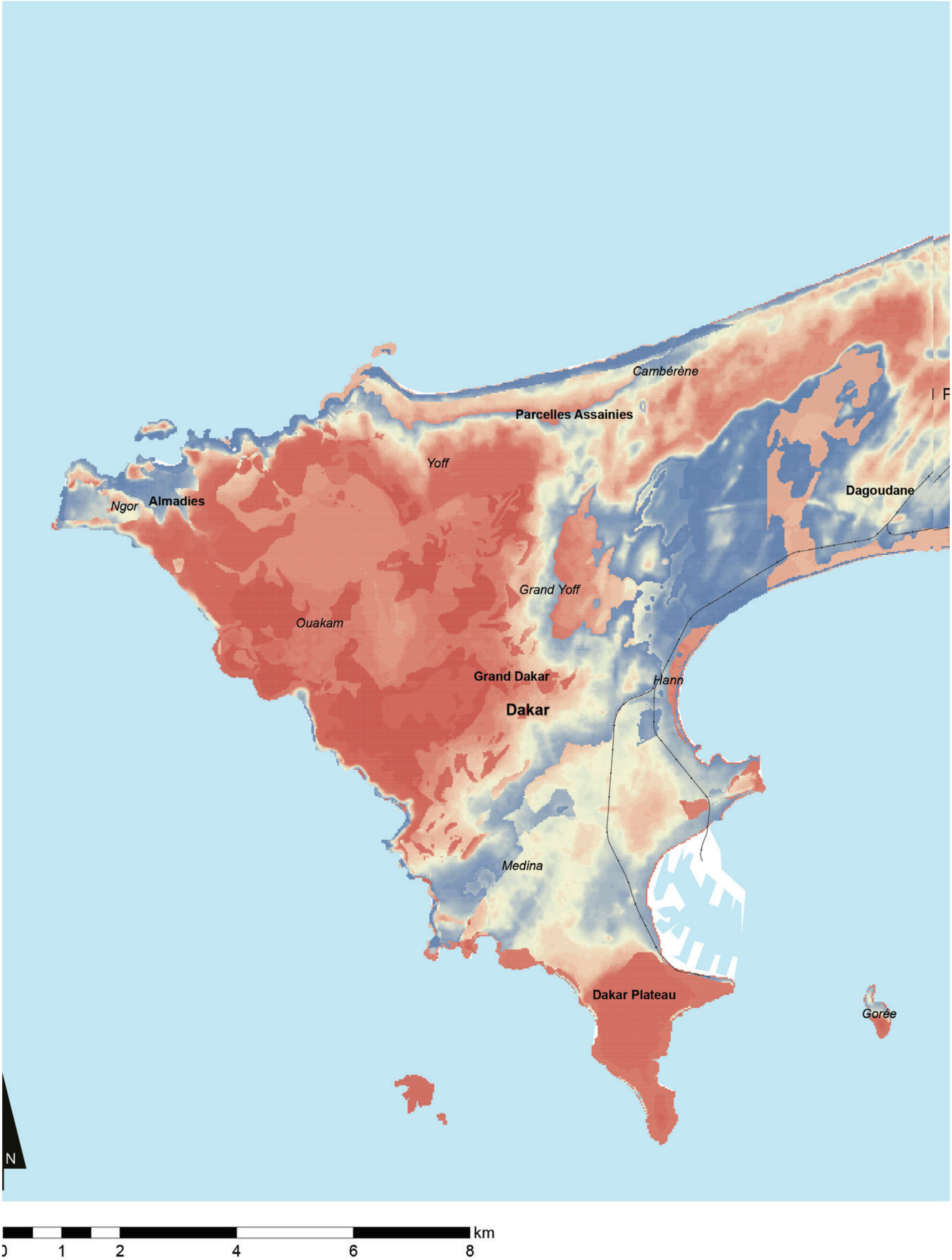


Figure 3.3.11. Resource potentials for space, geomaterials, groundwater and geothermal energy showing major differences between the Cap and the isthmus in the region of the *niayes*.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8

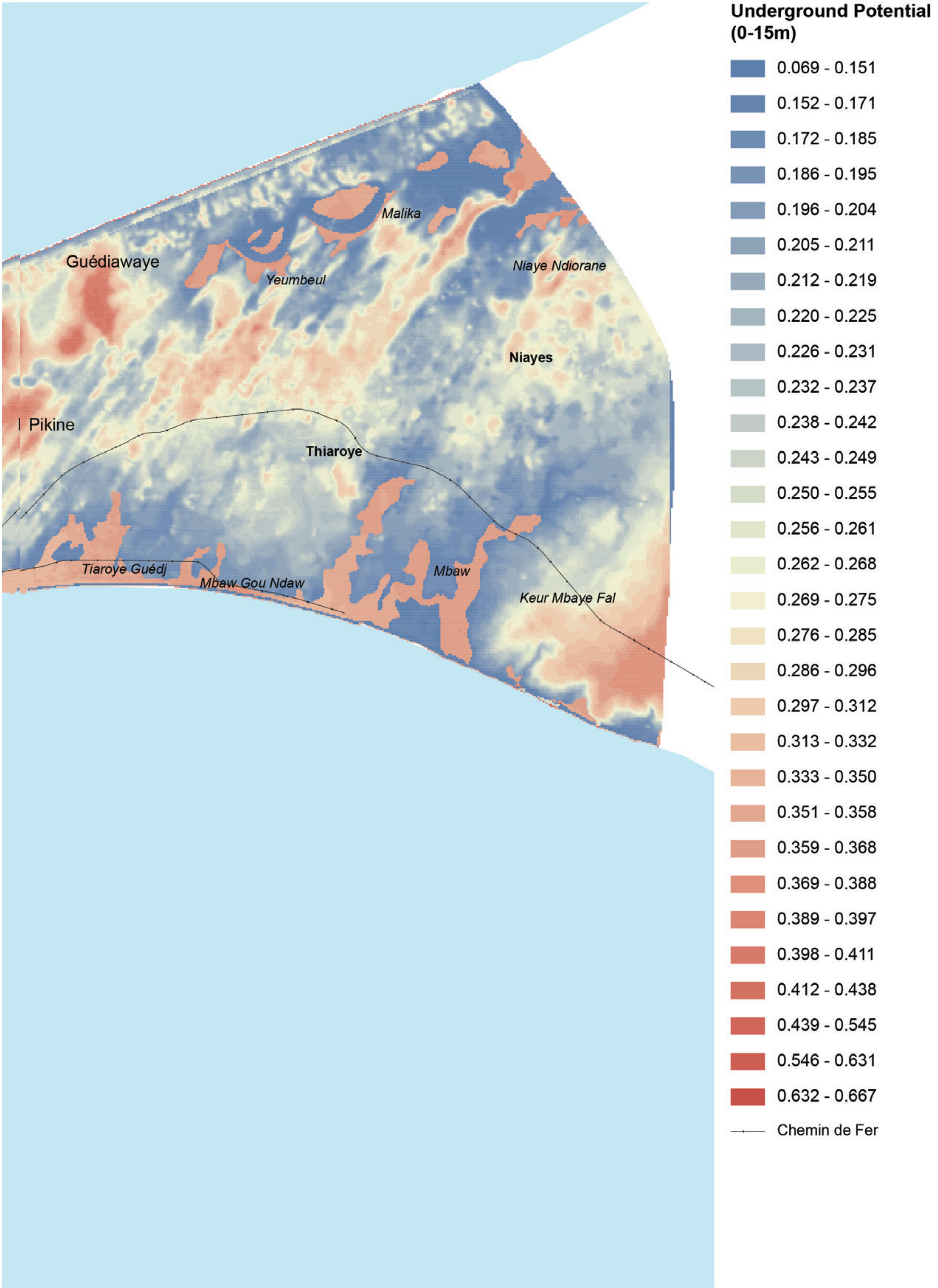
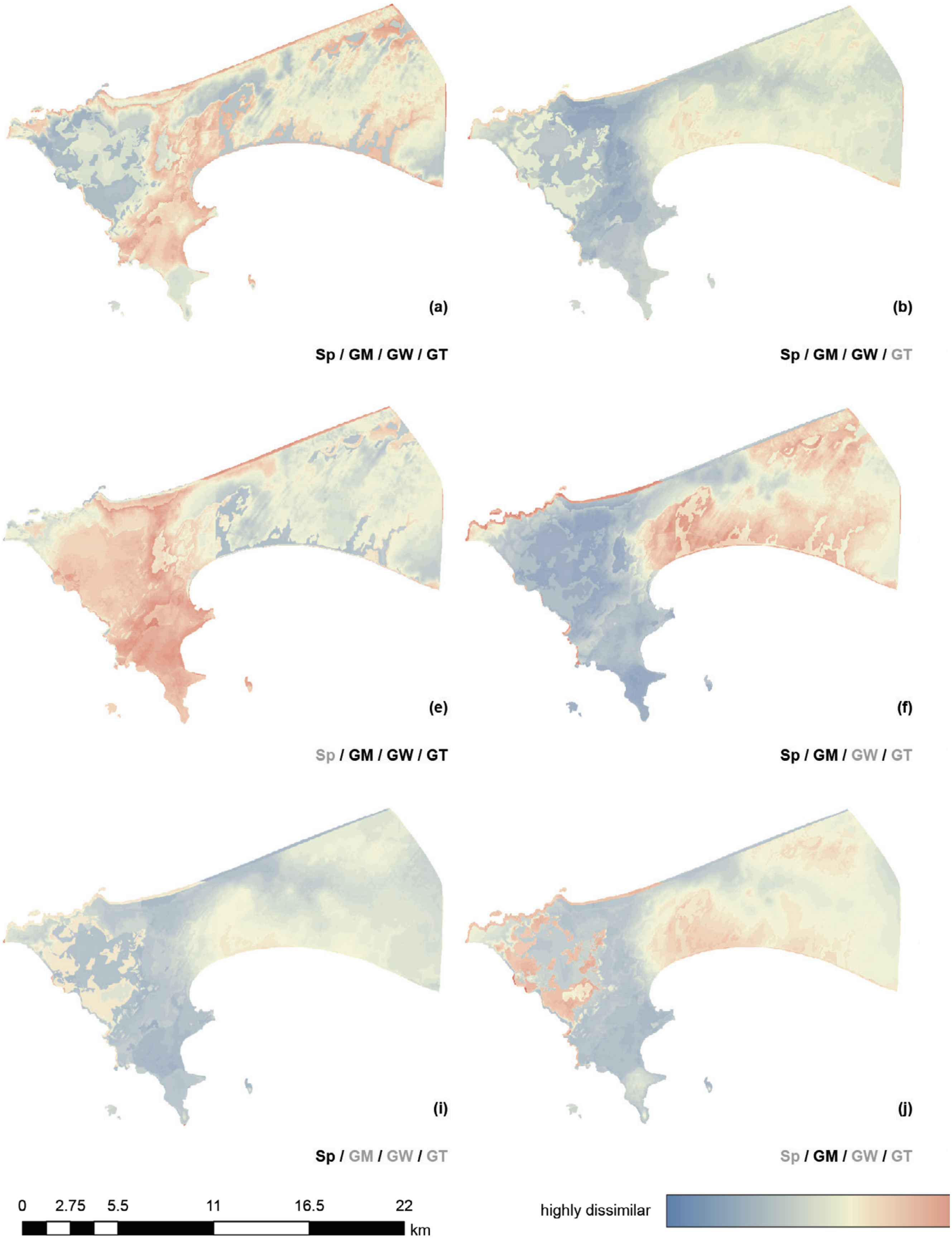


Figure 3.3.12. Combined underground potential at 0-15 meters. The areas of higher elevation and more stable geology tend to be higher.


(a)
Sp / GM / GW / GT
(b)
Sp / GM / GW / GT
(e)
Sp / GM / GW / GT
(f)
Sp / GM / GW / GT
(i)
Sp / GM / GW / GT
(j)
Sp / GM / GW / GT
0
2.75
5.5
11
16.5
22
km
highly dissimilar

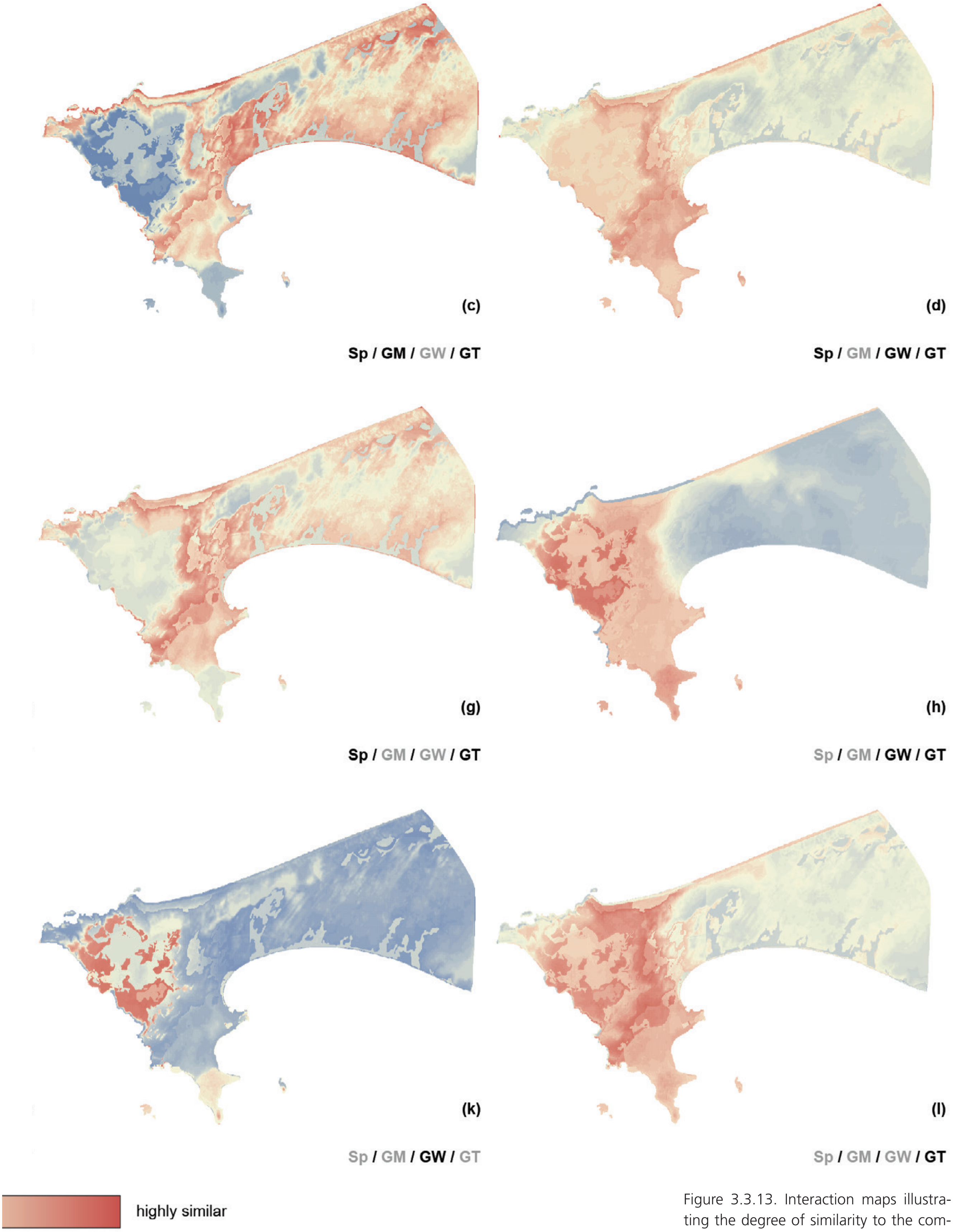


Figure 3.3.13. Interaction maps illustrating the degree of similarity to the combined resource potential categories.

Médina up the central parts of Dakar along the edge of the Yoff Plateau. These are likely to be the areas of greatest conflict, but also greatest synergy. The southern tip of the Cap, towards The Plateau and Cap-Manuel, would have to handle interactions between geothermal, groundwater and underground space. The current construction site for the parking garage beneath the Place de l'Indépendance is evidence of this interaction—water is being removed by pumps while diaphragm walls are being installed.[37] Geothermal, unfortunately is not part of the project and constitutes a lost opportunity. The Yoff Plateau would have to manage a high groundwater and geothermal potential (looking at (h)), but any construction project might be able to capitalize on a geomaterial synergy with space construction, although in that case all resource potentials would need to be addressed (given (a)). There are few areas that are very strongly oriented towards single uses, except for groundwater potentials on some parts of the plateau (above the infrabasaltic aquifer) and for geothermal (on almost the whole cap). However, the collection of interaction maps reveal that few areas can be easily zoned for one single resource.

Without delivering prescriptive statements about necessary directions or solutions for planning, the maps shed an alternative light on some of the observations made by the Horizon 2035 master plan. One of the main challenges faced by Dakar continues to come from its proximity to sea level and to two freshwater aquifers, one of which has been the source of damaging floods in some of the densest areas, most recently in 2012. As strategies are drawn up at the community level (via several NGOs) to the municipal (ADM) or national levels (DGPRE), it would be unfortunate for the full potentiality of the underground to go unaddressed. Not only because the construction of underground infrastructure for flooding could provide valuable geomaterials or opportunities to install geothermal collectors, but also because certain development decisions made in the short-term might prevent future opportunities. As history has shown, each master plan drawn up for Dakar has been based on underestimated levels of population growth. The transport network is congested and unpredictable. Even if there is no short term opportunity for an underground transport system, the planning process could already prepare for the areas where the network would run, the centers linked by it and the interactions that would need to be addressed throughout the city. With an underground transport system comes the opportunity to develop and network underground spaces, which are not just technical solutions, but reconfigure the economy of communication (of encounter and avoidance) of the socio-spatial fabric of a city. The maps of underground potential reveal the multiple directions that could be taken by the city, but Dakar is responsible for choosing the direction to go.

[37] As on a recording of the installation of diaphragm walls by the company Terratest available as of August 26th, 2016 : http://www.terratestnigeria.com/video/parking-place-de-lindependence-dakar.mp4.

3.3.6. Conclusion and Summary

This section of chapter 3 investigated the underground potential of Dakar in the West African country of Senegal. As highlighted in the beginning of this chapter, underground urbanism in Africa has received little attention by the research community. Dakar is also a particular complex case for evaluating underground potential not only due to its presence on a peninsula, which limits its directions of expansion, but also due to its proximity to the sea and position over two important aquifer systems supplying most of the city's drinking water. This situation means that a certain amount of data is available in various departments about the geology, the groundwater systems and the general conditions of the urban fabric and communication system. The evaluation of potential proceeded as in the San Antonio case study with the geological formations first converted in geotypes before evaluating their potentials for space, geomaterials, groundwater and geothermal energy. Unique to the Dakar case study was the involvement of local experts in the process and the testing of a clustering method for facilitating the pairwise comparison process. Also taken further from the two previous case studies was the production and interpretation of interaction maps, which reveal the different distributions of possible areas of conflict or synergy between the resources.

Several aspects were not able to be incorporated into this case study. The amount of involvement needed for local experts to evaluation the geotypes meant that it was not possible to then ask them to evaluate the relative weights of each criteria. This led to the aggregation process not weighting the criteria that contributed to the overall resource potentials. This has its advantages and disadvantages, but both alternatives should be tested and compared. For instance, the urban centrality metrics do not contribute as highly as they did in the San Antonio or Hong Kong case studies, where they were given a relatively high criteria weight. Alternative weights would have to be tested in collaboration with local experts. The next step would be to return to Dakar with these initial maps and to present them to local experts who participated in the comparison process. Then the maps could be presented to groups of local urban planners from the public and private sectors along with the geologist and geotechnical engineers who participated in their elaboration, to get feedback on both the legibility of the maps but also on the potentiality itself and what it means for their particular vision of the planning objectives of the city. Resource potential would be presented prior to formulating particular needs. In this way the maps would be pivot points for interdisciplinary discussions. It was evident when visiting Dakar that people are working separately on common problematics. The potential maps would provide a common visual ground for discussing Dakar's underground potential from multiple angles.

Chapter 4

Conclusion

Harnessing the Potentiality of the Urban Volume

Si la boussole, vrai géométral, ou rose des vents, posée là, était, non seulement passive, mais active: si elle était un gouvernail?

[…]

Et si nous avions—Noël!—la liberté de recaler le gouvernail, de changer de cap…?"

- Serres, *Rome* (1983)

"What if the compass, true geometral, or compass rose, placed there, was not only passive but active; what if it was a rudder?

[…]

And what if we—hallelujah—had the freedom to fix the rudder anew, to change course..?"

- Serres, *Rome* (2015)

When city planning and design reflect upon future forms of urbanity, the underground is perceived as a source of constraint and obstacles, not of opportunity. It remains a last resort, of interest only when all alternatives have been exhausted. Experience, however, has shown that treating the underground in this fashion can prevent an urban area from maximizing opportunities and minimizing conflicts.[1] On the one hand, this is because the underground has been addressed as an abundant resource, whose scarcity is only recognized once competition for the little amount that remains bars (or renders costly) additional projects and alternative uses. On the other, the only underground resource that has mattered for cities, citing Hénard, Utudjian and others, is space.[2] International organizations today continue to promote the benefits of underground space for urban areas, forgetting (or placing a lesser importance upon) other resources such as groundwater, geothermal energy and geomaterials. A sustainable strategy challenges cities to think in terms of multiple resources and uses.

The subsurface is not by nature a passive repository for the unsightly nor the hostile opposition to surface urbanity. Dominant practices have merely defined it and continue to define it as such. The subsurface is the physical (and sometimes mythical) ground upon which our cities are founded. Organizations such as the International Tunneling Association's Committee on Underground Space as well as the Associated Research Centers for Urban Underground Space have made it their mission to promote a reflection on underground space at the strategic phases of urban planning.[3] More even than

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1 Pascal Blunier, "Méthodologie de Gestion Durable Des Ressources Du Sous-Sol Urbain" (Doctoral Dissertation, EPFL, 2009), http://library.epfl.ch/theses/?nr=4404.

2 Eugène Hénard, *Etudes Sur Les Transformations de Paris, et Autres Écrits Sur L'urbanisme*, Collection "Formes Urbaines" (1903; repr., Paris: L'Equerre, 1982); Edouard Utudjian, *L'urbanisme souterrain.* (Paris: Presses universitaires de France, 1952).

3 International Tunnelling and Underground Space Association, "Report on Underground Solutions for Urban Problems," April 2012.

the legal, political, social or psychological consequences and hurdles facing underground projects, these organizations understand that the underground remains forgotten if it cannot be rendered visual in the language to which planning is accustomed—two-dimensional maps. As planning practices adopt three-dimensional tools for visualizing the relationships between the city and its environment, the geological models that some city departments are drawing up will become a common input for the planning process. Such models, however, are not yet commonplace.

Several cities are considered pioneers in the mapping and master-planning of underground space. Helsinki has previously completed, and Hong Kong has nearly completed, masterplans that identify areas of the city where the geological conditions are suitable for building large cavern spaces.[4] Although the city of Montreal has never explicitly incorporated the Indoor City into its masterplans, the addition of underground corridors linking new developments to the existing network is promoted through guidelines.[5] Several cities in China, where urban areas are experiencing demographic booms (due to migration from the countryside) are drawing up masterplans. The example presented in Chapter 1 of Qingdao illustrates the level of sophistication that such master-planning can take, from the number of criteria chosen to the methods used to evaluate them quantitatively.[6]

Existing mapping methods, however, have several limits. They are typically based on a single resource (space). In evaluating the ground conditions, the presence of groundwater, other than influencing the space potential, is not taken into consideration as a separate resource, particularly in locations where the groundwater is not an important source of drinking water. The potential uses of geomaterials extracted during excavation do not often influence the evaluation of space suitability. Where the geothermal opportunities are poorly known (even by geologists) and alternative sources of energy remain widely available and inexpensive, the temperature gradient or conductive properties of the geology are not integrated into the mapping process. The primacy given to space can be attributed to the sectorial nature of the investigation of the underground. Groundwater and geothermal energy are the purview of different departments and disciplinary expertise. Engineers tend to be the promoters of underground infrastructural projects that respond to obstacles caused by competing resources as technical problems.

[4] Ilkka Vähäaho, "An Introduction to the Development for Urban Underground Space in Helsinki," *Tunnelling and Underground Space Technology* 55 (May 2016): 324–28; M.I. Wallace and K.C. Ng, "Development and Application of Underground Space Use in Hong Kong," *Tunnelling and Underground Space Technology* 55 (May 2016): 257–79.

[5] Michel A Boisvert, *Montréal et Toronto : villes intérieures* (Montréal: Presses de l'Université de Montréal, 2011); Ahmed El-Geneidy, Lisa Kastelberger, and Hatem T. Abdelhamid, "Montréal's Roots: Exploring the Growth of Montréal's Indoor City," *Journal of Transport and Land Use* 4, no. 2 (August 18, 2011): 33–46.

[6] Jing-Wei Zhao et al., "Advances in Master Planning of Urban Underground Space (UUS) in China," *Tunnelling and Underground Space Technology* 55 (May 2016): 290–307.

Furthermore, existing patterns of urbanization are treated as passive demand for underground space. Indeed, population and built densities as well as land prices are good indicators for places where underground space is most needed, particularly when compact or high-density development strategies choose (or are forced by building height restrictions) to place activities underground. However, the geometry of the existing urban form and the distribution of activities condition the capacity for future activities to be easily accessible at multiple distances. As such, current patterns of urbanization constitute a supply (or potential) to be taken into consideration in the long-term. Although not as constraining as the geology (which is difficult or impossible to radically change), the transformation of the relationships between places in the city as established by the urban geometry tends to occur gradually and can be regularly updated as its supply capacity evolves.

The Deep City project proposes an alternative paradigm oriented towards the evaluation of underground resource potentials prior to thinking in terms of needs.[7] It places necessity on a more distant horizon. Deep City has investigated hypothetical scenarios in which underground projects are economically feasible.[8] It proposes a methodology for mapping underground resource potentials, which has been tested in Geneva and Suzhou, China. However, the 'needs to resources' paradigm has received little attention as a theoretical and philosophical framework. The use of the Analytic Hierarchy Process in the mapping carried out so far is oriented towards objectives that are needs-based. The research presented in the preceding chapters tried to respond to the current limitations of both the literature and the Deep City project, in focusing on theory and philosophy, spatial econometrics and the mapping of underground resource potential. This conclusion chapter will return to the main arguments and findings considering the results obtained and discuss opportunities for further research.

4.1. Resources to Needs: A Radical Change

As argued in Chapter 1, scientific inquiry tends to mistakenly give primacy to necessity over contingency. If the world and the things found in it exist, we presume that they must exist for a reason that can be deduced from a logical causality. Phenomena are modeled as systems and the relationships established between elements are addressed as universal. The Nobel laureate, Jacques Monod, demonstrated how, in more complex systems like organisms, necessity *follows* chance and contingency.[9] Referring to physicist

[7] A. Parriaux, L. Tacher, and P. Joliquin, "The Hidden Side of Cities—towards Three-Dimensional Land Planning," *Energy and Buildings* 36, no. 4 (April 2004): 335–41; A. Parriaux et al., *Projet Deep city : ressources du sous-sol et développement durable des espaces urbains* (Lausanne: vdf Hochschulverlag AG an der ETH Zürich, 2010).

[8] Pierrick Maire, "Étude multidisciplinaire d'un développement durable du sous-sol urbain. Aspects socio-économiques, juridiques et de politique urbaine" (Doctoral Dissertation, Swiss Federal Institute of Technology Lausanne (EPFL), 2011).

[9] Jacques Monod, *Chance and Necessity; an Essay on the Natural Philosophy of Modern Biology* (1971; repr., New York: Vintage Books, 1972).

Léon Brillouin's work on an information theoretical understanding of thermodynamics, Monod argued that complex systems require increasing amounts of information to maintain their highly improbable existence.[10] Systems evolve to more complex states because of changes that come about by chance and later, if they are reproduced, become rule-like—necessary.

Of course, cities are not organisms. They are a mixture of both artificial and natural processes, subjected as much to intentional interventions as they are chance circumstances. Inspired by Monod and Brillouin, Michel Serres argues that cities are, however, no less dependent (and maybe in some ways more so) upon information than organisms.[11] The quantity of information that cities generate and encode augments the possibilities and probabilities of alternative directions (like mutations) the city's evolution make take. This creates, like the crowd, a mass that is prior to necessity and ruled only by the law of chance.[12] It is a space before relations have settled and established structures. As Brillouin argued in the case of information, the increase in data available on the city comes with a price of increase in uncertainty. Serres claims that scientific practices are increasingly ignorant of this shadow of contingency that gets longer with increasing amounts of information.[13]

In dealing with chance as prior to necessity, the work presented here borrowed heavily from Serres's thinking on embracing uncertainty and the improbable, following Monod's claim that rational forms of scientific practice need not be totally abandoned.[14] Information is encoded in the materiality of things, which scientific inquiry has the mission to decode. For urban form, syntactical methods seek to interpret the social logic hidden in the geometry of the built environment, establishing the line and the void as the principal elements.[15] Urbanist David Grahame Shane examines how, in normative city models, the line (armature) and the void (enclave) have been subjected to necessary relationships based on dominant ideologies about ideal city form.[16]

In such normative models, necessity is given primacy to chance. The improbable and irrational are relegated to what Shane calls (borrowing from Foucault) heterotopias. In amusement parks and prisons, armatures and enclaves are reconfigured, reinvented, in ways that deal with the improbable. Paradoxically, in highly controlled environments, the rules can either be loosened (e.g. amusement

[10] Léon Brillouin, *Science and Information Theory*, Kindle Edition (orig. 1962), 2013.

[11] Michel Serres, *Rome: The First Book of Foundations*, orig. 1974 (1983; repr., London: Bloomsbury Academic an imprint of Bloomsbury Publishing Plc, 2015).

[12] Michel Serres, *The Birth of Physics* (1977; repr., Manchester: Clinamen Press, 2000).

[13] Michel Serres, *Le Passage Du Nord-Ouest*, Collection "Critique" 5 (Paris: Editions de Minuit, 1980).

[14] Michel Serres, *La Traduction*, Hermès 3 (Paris: Éditions de Minuit, 1968).

[15] Bill Hillier, *Space Is the Machine: A Configurational Theory of Architecture*, Electronic Edition (1996; repr., Cambridge: Cambridge University Press, 2007); Bill Hillier and Julienne Hanson, *The Social Logic of Space* (Cambridge: Cambridge University Press, 1984).

[16] David Grahame Shane, *Recombinant Urbanism: Conceptual Modeling in Architecture, Urban Design, and City Theory*, Kindle Edition (Chichester: Wiley-Academy, 2005).

parks) or strengthened (e.g. prisons). The armature, enclave and heterotopia are, however, addressed too much in a cybernetic fashion by Shane and do not fully exploit the potential Shane seeks in moving beyond the limitations of typo-morphology.[17] The first chapter introduced this problem as the difference between abstract and concrete universals.[18] To imagine that armatures, enclaves and heterotopias exist out of necessity or exist only as ideal forms errs on the side of abstract universality.

Instead, Shane's elements are addressed here as concrete universals that emerge from a contingency in the urban form. The syntactical approach proposed by Bill Hillier and colleagues is useful in understanding how linearity and convexity in urban form organize encounters and, referring to the recent work of Daniel Koch, avoidance.[19] Although Hillier claims that spatial syntax establishes an economy of movement, it is argued here that this movement economy is informed by an encompassing economy of communication, which organizes the contingency of encounters. It is an economy informed by both society and politics, but these remain downstream: First is an economy (the *oikonomia*), then a division and apportioning of it by the social and political.

Normative city models prescribe ideal forms for this economy, addressing certain relationships as necessary. The little attention given to the geological conditions of the urban volume suggests that the underground has avoided prescription. Per Shane, it is evident that the cosmological city, the mechanical city and the ecology city prescribe specific roles for the underground, when this latter is considered at all. Where it remains out of relation (unnecessary), these models cannot account for the underground's potential. Without prescription, it has no place in normative models. It is surprising to discover that, for all our interest in ecology as a language or logics (*logos*) 'found' in the world (*oikos*), its idealization of harmony and equilibrium places everything into relation and excludes that which is outside of relation.

Serres, in his reading of Lucretius and Monod, is interested in the contingent nature of existence, where the only necessity is chance itself. His account of agency in the world can be understood through three motors: the mechanical, transformational and informational.[20] Where the first two describe the types of agencies found in normative city models (with precisely defined reservoirs or stocks and the elements of the motor's workings), the informational motor troubles the stability of the stock, the reservoir, upon which the motor operates. If the first two motors describe a single point or

[17] David Grahame Shane, "Transcending Type: Designing for Urban Complexity," *Architectural Design* 81, no. 1 (January 2011): 128–34

[18] David Ellerman, "On Concrete Universals: A Modern Treatment Using Category Theory," *SSRN Electronic Journal*, 2014.

[19] Daniel Koch, "On Avoidance: Reflections on Processes of Socio-Spatial Structuring," *Civil Engineering and Architecture* 4, no. 2 (April 2016): 67–78..

[20] Michel Serres, *La Distribution*, Hermès 4 (Paris: Editions de Minuit, 1977).

a difference between two points, the informational motor adopts the any-point and the all-point.[21] For the mechanism of this latter, Serres proposes the *quasi-* (object, subject and collective). The quasi, which troubles the stability of identity, enables substitutions and recoding, working informationally.[22] After Brillouin, this information is material and comes with a price (no observation is gratuitous). This price is the increase in uncertainty and contingency.

This dissertation chose to hold necessity at a distance and to bear witness to potential as something latent and that comes with a price. This price is the responsibility toward the uncertainty and contingency generated. The methods adopted did not require throwing out existing rational methods, but rather (as Monod has proposed) using them to grasp at the irrational and the improbable—addressing geology and urban form as 'strange objects'.[23] It chose to observe the economy of communication as it was locally instantiated, as the result of contingency and chance, rather than a necessity born out of stable forms. Potential are the possibilities encoded in economies of communication, single directions. When those directions are multiplied, they become directionality and potential becomes potentiality. It is the increase in possibilities (and in the improbable) through the increase in information.

4.2. Potential of the Spatial Articulation of the Urban Volume

Where the first chapter laid out the general conditions for thinking resources before needs, the second chapter sought to investigate an economy of communication where necessities have *already* emerged from contingency. The most common type of urban underground spaces encountered are commercial establishments located around transit hubs and metro stations. In Montreal, these underground spaces are connected to a larger indoor network of pedestrian corridors that make up the Indoor City. The interiorization of public space in this fashion has been criticized by urbanists for drawing people away from the street.[24] Previous literature looking at the Indoor City has never considered it as part of a larger movement network, which includes the street, resulting in a lack of opportunity to examine the neighborliness of indoor and outdoor spaces.[25]

The second chapter sought to respond to the limits in previous studies by analyzing the spatial configuration of the Indoor City as inseparable from and embedded within a larger pedestrian network

[21] Vera Bühlmann, "Primary Abundance, Urban Philosophy—Information and the Form of Actuality," in *Printed Physics: Metalithikum I*, ed. Vera Bühlmann and Ludger Hovestadt, Applied Virtuality Book Series, v. 1 (Vienna: Springer, 2013), 114–54.

[22] Michel Serres, *The Parasite*, trans. Lawrence R. Schehr (1980; repr., Baltimore: Johns Hopkins University Press, 1982).

[23] Monod, *Chance and Necessity; an Essay on the Natural Philosophy of Modern Biology*, see in Chapter 1.

[24] David L. Uzzell, "The Myth of the Indoor City," *Journal of Environmental Psychology* 15, no. 4 (December 1995): 299–310.

[25] John Zacharias, "Underground Pedestrian Trips—trip Generation, Spatial Distribution and Activities in the Montréal Underground," *Tunnelling and Underground Space Technology* 46 (February 2015): 46–51; John Zacharias, "Modeling Pedestrian Dynamics in Montreal's Underground City," *Journal of Transportation Engineering* 126, no. 5 (September 2000): 405–12.

that includes streets, alleys and parks. To accomplish this, a three-dimensional spatial network model was built in ArcGIS of food and retail locations that were situated at street level or directly along corridors of the indoor network. While a good portion of this network is underground, it also includes corridors at ground level and at one and two levels above. Using the Urban Network Analysis Toolbox plugin for ESRI's ArcGIS, the spatial configuration of each food and retail location could be established as a combination of accessibility metrics at multiple network radii to adjacent commercial spaces, to pedestrians, to green areas (parks and tree canopy) and to housing units.

Rather than choose specific metrics, spatial configuration was conceived as something to decode from the mass of accessibility metrics—regularities identified within the informational mass of the Montreal downtown. The approach was necessary because it was evident in looking at previous spatial configurational studies on multi-level urban spaces that centrality was not reducible to a single metric, but rather tends to encompass several distances–pervasive centrality.[26] To establish pervasive centrality as concrete universals, the analysis adopted principal component analysis (PCA). Pervasive centrality would make it difficult to rely on the abstract universals of typo-morphological approaches, because it suggests that space (distance) and time (based on speed of walking) cannot be given. The use of PCA on multiple metrics allowed the analysis to remain indifferent to their combinations and permit pervasive centrality to emerge.

The analysis identified eight principal components that described different configurational combinations. Do there appear to be any major configurational differences between the indoors and outdoors? For the most part, the same regularities (rules) of encounter and avoidance tend to characterize the indoors and outdoors and reflect those that location theory has already identified for commercial spaces in terms of clustering to share spillover effects of comparison shopping. Even as indoor locations retreat somewhat from the street, forming interior clusters, the general proximity of outdoor commercial spaces means that the clusters almost always include outdoor locations adjacent to the indoor city. It is already a high proximity of outdoor commercial area that makes indoor food and retail locations able to expect certain spillover effects.

The major differences between the spatial configuration of indoor and outdoor corridors of food and retail are on their relationship to pervasive through-movement (betweenness) and topological (turns) to-movement encounter and avoidance. Indoor spaces tend to be situated off the beaten path (meaning less often on shortest paths between other locations in the network) at large

[26] Bill Hillier, "Spatial Sustainability in Cities: Organic Patterns and Sustainable Forms," in *Proceedings of the Seventh International Space Syntax Symposium*, ed. D. Koch, L. Marcus, and J. Steen (Stockholm: Royal Institute or Technology, 2009), K01.1-K01.20.

metrics, which means that are not as pervasively central in terms of through-movement, in comparison to outdoor locations. They are also situated on more serpentine paths, weaving from floor to floor along escalators or stairs. Where one or two turns in the street grid of Montreal can mean a high accessibility to other commercial locations or pedestrians, for indoor spaces, one or two turns may not even take the pedestrian to the next floor.

After highlighting the spatial configurations that characterized the heterotopiality of the Montreal Indoor City, spatial econometric methods were adopted to evaluate the impact of spatial configuration on rents per square meter (using data from 2004). The framework presented in Chapter 1 served to critically examine the use of the regression and borrowed from recent philosophical debates in economics in arguing for an approach that addresses the statistical model as the abstraction of a spatial contingency, rather than as the attempt to isolate mechanisms that are universal and generalizable.[27] Although the method ended up diverging slightly from more orthodox applications of spatial econometrics, the analysis had more freedom to explore configurational categories as concrete universals (and as improbable regularities) using the sophisticated experimental controls offered by spatial econometrics.

The results of the regression analysis revealed that, in the Montreal downtown, being indoors rather than outdoors tends to increase rent per square meter by nearly 50% when spillover effects are taken into consideration. All locations tend to benefit from being smaller in surface area, being within a five-minute walk (400m) from pedestrians and other commercial areas as well as being on shortest paths at multiple radii. It is particularly interesting to note that pervasive betweenness has the largest marginal effect on rent per square meter. A 5% increase in the degree of membership of a food or retail establishment to the configurational category would increase the rent by an additional 6 (for outdoor locations) to 18 $ CDN (for indoor locations) per square meter. Even though indoor places tend to be characterized less by pervasive centrality, it is important for the rental value generated by their location within the spatial network. It is no more to the advantage of indoor than outdoor food and retail establishments to be located off major arteries. This is another observation made by retail location theory of which this study found additional evidence for indoor retail locations.

Several improvements in terms of experimental production and control could be made for future research. With the quantity of data available for the Montreal downtown in the Observatory on the Indoor City's database, it would be beneficial to expand the analysis to include non-food and retail spaces. The model could capture a larger, more diverse, economy of avoidance and encounter.

[27] Amit Ron, "Regression Analysis and the Philosophy of Social Science: A Critical Realist View," *Journal of Critical Realism* 1, no. 1 (July 15, 2002): 119–42. ; Nuno Ornelas Martins, "Critical Realism, Econometrics and Heterodox Economics," in *Handbook of Research Methods and Applications in Heterodox Economics*, by Frederic Lee and Bruce Cronin (Cheltenham, UK: Edward Elgar Publishing, 2016), 222–36.

Furthermore, the configurational analysis could test alternative methods to account for pervasive centrality. Although principal component analysis was adopted here, it remains a data reduction function relying on linearity in the data (taking the line as an abstract universal). As mentioned in the conclusion to Chapter 2, non-parametric methods such as self-organizing maps may prove more revealing. This may, however, require further adapting or abandoning spatial econometric methods altogether, which would raise questions in terms of the experiment control necessary to verify spillover effects and strategic interactions between the spaces included in the regression model.

The results of the Montreal analysis do not provide quick rules of thumb and paths of least resistance in developing successful underground spaces. In general, it appears advantageous to be well connected to both indoor and outdoor places, to develop a delicate balance of being central at certain metrics and being either part of central or peripheral clusters of places. Nevertheless, the ledgers of avoidance and encounter can never be perfectly balanced without oversimplification. The distributions of configurational categories and their varying contributions to rental values suggest that the economy of communication is robust to certain shifts and gradients in the metrics. It is not about being fully central or fully peripheral but rather about finding the in-between. Intervention in Montreal could play within these distributions of coefficients, articulating new corridors of encounter and removing others to reconfigure the potentiality of the permeability and connectivity of spaces. This would be interesting future work that could incorporate a more dynamic use of centrality metrics.[28]

4.3. The Geological Volume: Making Room for the Improbable

While the second chapter addressed in detail an established network of urban underground spaces, the third chapter returned to the territorial scale and a diagnostic evaluation, where underground space is one of four resources constituting the underground potential of an urban area. The application of the Deep City method to San Antonio, Hong Kong and Dakar sought to not only make improvements to the mapping method, but also to challenge the current limits of other mapping methods. The paradigm of 'resources to needs' seeks to delay the influence of necessity on the evaluation of resource potentials, which for this dissertation entailed testing the method on cities where needs would not overshadow the evaluation of potential. The paradigm also challenged the methods used to quantify expert knowledge.

Deep City San Antonio and Deep City Dakar applied the resource potential evaluation and mapping method to two cities that are currently not looking to underground solutions for the

28 This is possible with the UNA Toolbox, thanks to its recent porting to the Autodesk Rhino software where 3D models can be built and their centrality metrics calculated dynamically.

challenges they face. Both cities have a complicated relationship to their underground resources, given the importance and presence of an aquifer providing most of the city's drinking water. The evaluation of potential in both case studies worked from geotype descriptions of the geological formations identified on geological maps of the superficial and substrate formations. The Analytic Hierarchy Process served to capture expert knowledge in order to provide a general knowledge of the characteristics of the city's geology, without requiring more detailed data that has yet to be collected or rendered publicly available.[29] Both the case studies of San Antonio and of Dakar demonstrated that the Deep City method is not only applicable to cities without complex models of their geology, but also to cities in both developed and developing countries. In theory, the only source of data needed is a geological map and a road or parcel map to provide a useful evaluation.

Deep City Hong Kong tested the resource potential evaluation and mapping method in a city where the interest in underground space is founded upon necessity. Although other resource potentials are excluded in prioritizing space, the mapping method provided by Deep City to complement Arup and Associates' cavern master plan expands the potentiality of the caverns to their possible integration with subsurface spaces beneath existing urban areas. The adjacent urban form is no longer a static given, but a relational field to which future cavern portals could be attached. The relational field (part of Hong Kong's economy of encounter and avoidance) drew upon aggregate resident and employment counts. Future work could include more fine-grained data or additional information for representing the potential of the existing urban form. Alternative criteria would also permit orienting the evaluation of centrality and accessibility in terms of other urban activities. This dissertation focused principally on commercial activities for future underground spaces.

Delaying the turn to needs and focusing exclusively on resource potentials poses challenges for the aggregation of layers in combining criteria and resource potentials. The Deep City method, like several other proposed methods presented in Chapter 3, adopts a multi-criteria approach that sets the criteria into a hierarchy and weights the aggregation process by priority weights.[30] In other mapping methods, priorities are established based on well-defined outcomes or objectives. This dissertation sought to keep objectives relatively vague, choosing to maximize one or several potentials. Once the potential has been evaluated, then questions of necessity can come

[29] Thomas L. Saaty, "How to Make a Decision: The Analytic Hierarchy Process," *European Journal of Operational Research* 48, no. 1 (September 1990): 9–26.; Thomas L. Saaty and Luis Gonzalez Vargas, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*, 2. ed, International Series in Operations Research & Management Science 175 (New York: Springer, 2012).

[30] Zhao et al., "Advances in Master Planning of Urban Underground Space (UUS) in China"; Jian Peng, Yang Wang, and Fangle Peng, "Evaluation of Underground Space Resource for Urban Master Plan in Chanzhou City," in *Underground Space: Planning, Administration and Design Challenges* (ACUUS 2014, Seoul, South Korea, 2014), 30–35.

into play. This is the important separation between potential as constitutive of an existing economy of communication and the role of the political and social to differentiate such an economy into their anthropocentric logic of encounter and avoidance.

Aggregation by simply adding layers is, however, difficult to interpret, which is why the dissertation proposed to evaluate resource potentiality by the degree of proximity to possible combinations of potentials. This was first tested in San Antonio and then further explored in Dakar. In both cases, the analysis found that certain locations are characterized by a combination of resource potentials, which could either be synergetic if harnessed or conflictual if dealt only in terms of a single resource. Further work should test the utility and ease of interpretation of the interaction maps with practitioners and decision-makers. It may not be obvious at first what combined potentials entails and how it does not prescribe, but only indicates. This is what is meant when, as argued in Chapter 3, the map is meant as a compass. It indicates directionality but only as the integral of several directions. It must be subjected to the discussion and debate that typically accompanies the planning process.

Further work is also needed on the participation of local experts in the evaluation of resource potentials. The pairwise comparison process proposed by the AHP is no small matter, and the participation of local experts needs to be planned to collect responses in a timely fashion and to brief participants on the geotypes adopted and the exercise to be performed. It also has its limits in that certain expert knowledge is lacking. In Dakar, this was most evident for the geothermal potential of local geology, which does not only rely on the temperature of the ground, but rather on the conductive properties of the geological formations, for installing low-enthalpy systems. As the geothermal technology becomes more sophisticated and more widely available, the ability to harness geothermal potential will only increase.

4.4. The Urban Volume: Lessons for Practical Application

Although each of the three cities where potential was mapped—in their geology, decision-making structures and procedures and their political and economic climates—is different, there are several common conditions that will facilitate the operationalization of the interaction maps in the planning process. First, data collection should be cross-departmental yet centrally controlled. Each project or site investigation should be submitted to the city GIS database. This includes drawing up standards for data collection. This dissertation showed that the maps can be produced without recourse to onerous quantities of data. But more and more rigorously compiled data would improve them. Second, if the data is centralized, the underground potential and interaction maps should not be. The process of evaluation of geological potential is certainly not the sole purview of geologists, but geologists do have the responsibility of becoming the stewards of the maps.

Third, a sustainable management of underground resources means considering all four of them, where they exist and regardless of their current significance. In San Antonio, discussions with local decision-makers suggested that the public sector did not want to be responsible for managing geomaterial use, even if their use could be something that public policy encouraged. Perhaps more private sector involvement will be necessary with public sector encouragement. In Switzerland, the company Terrabloc has been working with construction sites to use excavated materials to produce terra cotta blocks, reducing the amount of material to be placed in landfills.[31] The underground potential maps would help in identifying the sites where contractors would have the greatest interest in contacting companies like Terrabloc. The potential maps indicate areas where there are likely local aquifers or where the water table is high. In certain situations, it may be of interest to coordinate with the local water management system and permit local extraction, for example, for irrigation. Geothermal energy is often given too little attention because fossil fuels remain cheap, although geothermal is only second after photovoltaic in being a renewable resource harvesting solar energy indirectly through the earth's crust. When placing resources before needs, geothermal energy will increasingly be harvested as a competitive (and cleaner) alternative to petroleum and natural gas.

Finally, the interaction and potential maps would need to be integrated into any form of territorial diagnostic conducted prior to or during the planning process. Part of centralizing the data collection is making the maps easier to produce using richer data sets, but the maps themselves need to be readily available for use by interested parties. In San Antonio, the underground would be addressed in the long-term. In Hong Kong, this would be the short-term and, Dakar, the mid-term. The message would not be to develop the underground at all costs, but to consider it where density is being increased, as an alternative to surface development and as an opportunity to preserve parks and green spaces. The potential maps would serve to identify the areas of greatest interest and then the interaction maps would show which other resources are present. In some cases, the underground would be off-limits. Like aquifer recharge protection zones, it may be a question of a potential of high value. But it can also be a question of protecting a resource, like geothermal in many places, for which there is more potential than current demand. In zones of high underground construction and geothermal potential, any excavation project may be required to not only ensure that the excavated materials can somehow be used

31 http://www.terrabloc.ch

on site (or elsewhere), but also to make use of the local geothermal potential and reduce reliance on non-renewable sources.

Reversing the needs to resources paradigm in addressing underground resources means exposing first the potentiality of the urban volume, before exploring possible applications and projects. The maps, like compasses, can orient the planning process in regards to the multiple uses and potentiality of this volume. Only after constituting the reservoir of potentiality can design begin to play with these potentials, imagining new and novel forms of urbanity, from underground space to the harvesting of energies, water for urban agriculture or alternative drinking sources, and materials for local construction. It is then that a rudder emerges, a possibility to steer towards an alternate urban future. For the city to maintain its delicate imbalance, to be sustainable and resilient, its maintenance practices must be able to evolve and to incorporate novelty and the unknown. The underground has always been a sometimes silent, sometimes noisy contributor to these practices. It is not a question of condemning it to silence, but rather of finding unheard opportunities in the noise.

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Appendices

Appendix 3.2.1. Pairwise comparison questionnaire for experts at ARUP Associates in Hong Kong

The following questionnaire was given to two geologists and a civil engineer working on the cavern master plan. They were asked to return the questionnaire within the same day and not to consult each other in formulating their responses to the pairwise comparisons. In accordance with the Analytic Hierarchy Process, the favorability of each criterion in relation to its pair adopts a scale of 1 to 9.

In producing the questionnaire, the emphasis was explicitly placed on a basement underground development, which, for the Arup team, generates a different appreciation of what they define as soft (unconsolidated) and hard (bedrock and consolidated) ground. Whereas cavern development prefers hard rock (in particular, granite) because of its structural stability, basement development (often using cut and cover methods) prefers soft, unconsolidated, geological formations that are easier to excavate, but require additional structural reinforcing.

Deep City Hong Kong

Pairwise Comparison Questionnaire for Geological and Physical Criteria

The objective of this pairwise comparison exercise is to elicit the relative importance of criteria used to identify suitable locations for ***BASEMENT*** *underground development in Hong Kong, as proposed by the Deep City Method developed at the Swiss Federal Institute of Technology in Switzerland. For any questions, do not hesitate to contact michael.doyle@epfl.ch.*

Please circle one of the two alternatives (A or B). If you do not feel confident answering for one of the pairs, please leave it blank.

For a given site and everything else equal, is it more favorable (for a basement development scenario) to be…

A. outside the 30 or 60 m protection zone around tunnels and MTR stations or
B. outside a zone where major flood incidents have been reported?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

Guide for this first question: If A is more favorable than B, circle A. How much more favorable is it? Please indicate on the scale of 1 to 9 whether it is equally or significantly more favorable.

A. outside the 30 or 60 m protection zone around tunnels and MTR stations or
B. within a zone of rock suitable for aggregate?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. outside the 30 or 60 m protection zone around tunnels and MTR stations or
B. in an area where the soft, easier to excavate ground is at least 30m deep?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. outside the 30 or 60 m protection zone around tunnels and MTR stations or
B. in an area without any corestones (class III rock)?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

Deep City Hong Kong

A. outside the 30 or 60 m protection zone around tunnels and MTR stations or
B. to be in a zone where current slope is favorable for basement development?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. within a zone of rock suitable for aggregate or
B. outside a zone where major flood incidents have been reported?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. in an area where the soft, easier to excavate ground is at least 30m deep or
B. outside a zone where major flood incidents have been reported?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. in an area without any corestones (class III rock) or
B. outside a zone where major flood incidents have been reported?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. in a zone where current slope is favorable for basement development or
B. outside a zone where major flood incidents have been reported?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. within a zone of rock suitable for aggregate or
B. in an area where the soft, easier to excavate ground is at least 30m deep?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. within a zone of rock suitable for aggregate or
B. in an area without any corestones (class III rock)?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. within a zone of rock suitable for aggregate or
B. in a zone where current slope is favorable for basement development?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. in a zone where current slope is favorable for basement development or
B. in an area where the soft ground is at least 30m deep?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. in an area where the soft ground is at least 30m deep or
B. in an area without any corestones (class III rock)?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

A. in a zone where current slope is favorable for basement development or
B. in an area without any corestones (class III rock)?
And how much more favorable is it?

Equally favorable 1 2 3 4 **5** 6 7 8 9 Significantly more favorable

Thank you very much for taking the time to respond.

Appendix 3.3.1. Preliminary grouping exercice for experts in Dakar

The following questionnaire was sent to nine experts who were recruited during a two-week stay in March 2016 in Dakar. This included a hydrogeologist at the *Direction de la gestion et de la planification des ressources en eau*, which handles water resource management, a hydrogeologist from the *Agence développement municipal*, a planning agency, an ecologist from the *Centre de suivi écologique*, a geologist from a private consulting company, two professors of geomorphology at the University of Dakar, a professor of hydrogeology at the University of Dakar, a geologist from the *Institut des sciences de la terre* at the University of Dakar and a geologist from the *Centre expérimental de recherches et d'études pour l'équipement*, a research centre for public infrastructure. Of those invited, only a professor of geomorphology and a hydrogeologist responded to this questionnaire. The geologist co-supervisor of this dissertation also particpated. It took respondents anywhere from 15 to 25 minutes to complete, depending on the number of sections they chose to respond to. The geomorphologist chose not to respond to questions on the geothermal potential and the hydrogeologist opted out of the questions on geomaterials.

Quel est le potentiel d'utilisation et de valorisation de la géologie de Dakar?

C'est une question qui dépend de l'expérience de scientifiques et de praticiens comme vous qui savez comment en réalité (sur le terrain) se comportent les formations géologiques.

Pour ce faire, le projet Deep City à l'EPFL a adopté une méthode qui permet de situer chaque famille de formations géologiques sur une échelle relative d'aptitude. Vos réponses nous permettront de produire des cartes de potentiel que nous partagerons avec vous et avec des urbanistes de la ville de Dakar.

Démarrer

Sur la presqu'île de Dakar, nous observons plus qu'une trentaine de formations géologiques différentes, de marnes et argiles aux sables humifères et éoliens. Pour simplifier l'exercice, nous les avons réduits à dix familles géologiques que nous nommons des *géotypes*

Géotypes	Formations géologiques
APA – Alluvions des plaines	Fz (argile, sable et cailloutis) CF (sable argileux)
EOL – Sables dunaires	Sables rubéfiés (Dv-y), dunes blanches (Dlz4) et dunes jaunes (Dlz3)
GR – Grès	Grès calcaire coquillier (My)
LS – Sables littoraux	Sable coquillier (Sgz), des plages (Mz2-4) et des cordons littoraux
P – Dépôts palustres	Sables humifères (FTz, Tz)
LAV – Laves	Coulées de hawaiite (d5ß, m5ß, scn5ß), de basanite (4ß, 3ß)
M – Marne	Argiles et marnes (e4a, e2b, e1-3a)
MC – Alternance de Calcaires et de Marne	Alternances de marno-calcaires (e5b, e5c, e4b5, e4b1-4)
CA – Calcaire Argileux	Calcaires coquillers et marnes (e1) ; Calcaires argileux, marno-calcaires
PYR – Roches pyroclastiques	Tufs volcanites (5tf, scr5tf, 3tf, 2tf)

Nous vous poserons des questions sur le potentiel d'utilisation des géotypes pour quatre ressources: l'espace, les géomatériaux, l'eau souterraine et la géothermie. Si une de ces ressources se trouvent en dehors de vos compétences, vous aurez la possibilité de la sauter.

1 Cette première partie sollicite votre appréciation du potentiel des géotypes pour la construction d'espace souterrain.

Si vous préférez ne pas répondre pour cet usage, veuillez cliquer sur "Non" *

Une boîte de texte se trouve à la fin de cette section pour toutes commentaires que vous avez à propos de votre appréciation.

○ Oui ○ Non

Comment évalueriez-vous le potentiel des Alluvion des plaines (APA) pour la construction d'espace souterrain?

APA : argile, sable et cailloutis (Fz) et sable argileux (CF)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Sables dunaires (EOL) pour la construction d'espace souterrain?

EOL : sables rubéifiés (Dv-y), dunes blanches (DIz4) et jaunes (DIz3)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Grès (GR) pour la construction d'espace souterrain?

GR : grès calcaire coquillier (My)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Sables littoraux (LS) pour la construction d'espace souterrain?

LS : sable coquillier (Sgz), des plages (Mz2-4), et des cordons littoraux

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Dépôts palustres (P) pour la construction d'espace souterrain?

P : sables humifères (FTz, Tz)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Laves (LAV) pour la construction d'espace souterrain?

LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Marnes (M) pour la construction d'espace souterrain?

M : argiles et marnes (e4a, e2b, e1-3a)

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Marno-calcaires (MC) pour la construction d'espace souterrain?

MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Calcaires argileux (CA) pour la construction d'espace souterrain?

CA : les calcaires coquilliers et marnes (e1)

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Roches pyroclastiques (PYR) pour la construction d'espace souterrain?

PYR : tufs volcanites (5tf, scr5tf, 3tf, 2tf)

0 1 2 3 4

Aucun potentiel — Moyen potentiel — Fort potentiel

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12 Avez-vous des commentaires à nous communiquer à propos de votre évaluation?

Sinon, appuyez sur "Entrée"

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13 Maintenant nous nous intéressons à votre appréciation du potentiel des géotypes pour un autre usage: les géomatériaux--c'est-à-dire leur potentiel à être valorisé sur ou hors-site dans le remblai, les agrégats ou autre.

Si vous préférez ne pas répondre pour cet usage, veuillez cliquer sur "Non" *

Une boîte de texte se trouve à la fin de cette section pour toutes commentaires que vous avez à propos de votre appréciation.

Oui Non

Comment évalueriez-vous la valeur des Alluvion des plaines (APA) comme géomatériaux?

APA : argile, sable et cailloutis (Fz) et sable argileux (CF)

0 1 2 3 4

Aucune valeur — Moyenne valeur — Importante valeur

Comment évalueriez-vous la valeur des Sables dunaires (EOL) comme géomatériaux?

EOL : sables rubéifiés (Dv-y), dunes blanches (Dlz4) et jaunes (Dlz3)

0 1 2 3 4

Aucune valeur — Moyenne valeur — Importante valeur

Comment évalueriez-vous la valeur des Grès (GR) comme géomatériaux?

GR : grès calcaire coquillier (My)

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

Comment évalueriez-vous la valeur des Sables littoraux (LS) comme géomatériaux?

LS : sable coquillier (Sgz), des plages (Mz2-4), et des cordons littoraux

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

Comment évalueriez-vous la valeur des Dépôts palustres (P) comme géomatériaux?

P : sables humifères (FTz, Tz)

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

Comment évalueriez-vous la valeur des Laves (LAV) comme géomatériaux?

LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

Comment évalueriez-vous la valeur des Marnes (M) comme géomatériaux?

M : argiles et marnes (e4a, e2b, e1-3a)

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

Comment évalueriez-vous la valeur des Marno-calcaires (MC) comme géomatériaux?

MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

Comment évalueriez-vous la valeur des Calcaires argileux (CA) comme géomatériaux?

CA : les calcaires coquilliers et marnes (e1)

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

Comment évalueriez-vous la valeur des Roches pyroclastiques (PYR) comme géomatériaux?

PYR : tufs volcanites (5tf, scr5tf, 3tf, 2tf)

0 1 2 3 4

Aucune valeur Moyenne valeur Importante valeur

24 À quels types de valorisation avez-vous pensé pour ces géotypes?

Pour passer à la prochaine question, appuyez sur ENTRÉE

25 Avez-vous des commentaires à nous communiquer à propos de votre évaluation?

Sinon, appuyez sur "Entrée"

26 Maintenant nous passons au potentiel des géotypes à être une source intéressante d'eau souterraine, par exemple pour l'irrigation ou de l'eau potable. Ceci est de manière générale à Dakar, en sachant que des différences existent localement.

Si vous préférez ne pas répondre pour cet usage, veuillez cliquer sur "Non" *

Une boîte de texte se trouve à la fin de cette section pour toutes commentaires que vous avez à propos de votre appréciation.

Oui Non

Comment évalueriez-vous le potentiel des Alluvion des plaines (APA) à être une source intéressante d'eau souterraine?

APA : argile, sable et cailloutis (Fz) et sable argileux (CF)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Sables dunaires (EOL) à être une source intéressante d'eau souterraine?

EOL : sables rubéifiés (Dv-y), dunes blanches (Dlz4) et jaunes (Dlz3)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Grès (GR) à être une source intéressante d'eau souterraine?

GR : grès calcaire coquillier (My)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Sables littoraux (LS) à être une source intéressante d'eau souterraine?

LS : sable coquillier (Sgz), des plages (Mz2-4), et des cordons littoraux

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Dépôts palustres (P) à être une source intéressante d'eau souterraine?

P : sables humifères (FTz, Tz)

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Laves (LAV) à être une source intéressante d'eau souterraine?

LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Marnes (M) à être une source intéressante d'eau souterraine?

M : argiles et marnes (e4a, e2b, e1-3a)

0	1	2	3	4

Aucun potentiel — Moyen potentiel — Fort potentiel

Comment évalueriez-vous le potentiel des Marno-calcaires (MC) à être une source intéressante d'eau souterraine?

MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)

0 1 2 3 4

Aucun potentiel | Moyen potentiel | Fort potentiel

Comment évalueriez-vous le potentiel des Calcaires argileux (CA) à être une source intéressante d'eau souterraine?

CA : les calcaires coquilliers et marnes (e1)

0 1 2 3 4

Aucun potentiel | Moyen potentiel | Fort potentiel

Comment évalueriez-vous le potentiel des Roches pyroclastiques (PYR) à être une source intéressante d'eau souterraine?

PYR : tufs volcanites (5tf, scr5tf, 3tf, 2tf)

0 1 2 3 4

Aucun potentiel | Moyen potentiel | Fort potentiel

---

37 Avez-vous des commentaires à nous communiquer à propos de votre évaluation?

Sinon, appuyez sur "Entrée"

---

38 Le dernier usage qui nous intéresse est la géothermie, ce qui peut être autant une solution pour refroidir les bâtiments que pour les réchauffer.

Si vous préférez ne pas répondre pour cet usage, veuillez cliquer sur "Non" *

Une boîte de texte se trouve à la fin de cette section pour toutes commentaires que vous avez à propos de votre appréciation.

Oui Non

Comment évalueriez-vous le potentiel des Alluvion des plaines (APA) à être un géotype intéressant pour l'installation de systèmes géothermiques?

APA : argile, sable et cailloutis (Fz) et sable argileux (CF)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Sables dunaires (EOL) à être un géotype intéressant pour l'installation de systèmes géothermiques?

EOL : sables rubéifiés (Dv-y), dunes blanches (Dlz4) et jaunes (Dlz3)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Grès (GR) à être un géotype intéressant pour l'installation de systèmes géothermiques?

GR : grès calcaire coquillier (My)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Sables littoraux (LS) à être un géotype intéressant pour l'installation de systèmes géothermiques?

LS : sable coquillier (Sgz), des plages (Mz2-4), et des cordons littoraux

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Dépôts palustres (P) à être un géotype intéressant pour l'installation de systèmes géothermiques?

P : sables humifères (FTz, Tz)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Laves (LAV) à être un géotype intéressant pour l'installation de systèmes géothermiques?

LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Marnes (M) à être un géotype intéressant pour l'installation de systèmes géothermiques?

M : argiles et marnes (e4a, e2b, e1-3a)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Marno-calcaires (MC) à être un géotype intéressant pour l'installation de systèmes géothermiques?

MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Calcaires argileux (CA) à être un géotype intéressant pour l'installation de systèmes géothermiques?

CA : les calcaires coquilliers et marnes (e1)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

Comment évalueriez-vous le potentiel des Roches pyroclastiques (PYR) à être un géotype intéressant pour l'installation de systèmes géothermiques?

PYR : tufs volcanites (5tf, scr5tf, 3tf, 2tf)

0 1 2 3 4

Aucun potentiel Moyen potentiel Fort potentiel

49 Avez-vous des commentaires à nous communiquer à propos de votre évaluation?

Sinon, appuyez sur "Entrée"

50 Quel est votre prénom et votre nom de famille?

Veuillez noter que votre nom et prénom resteront confidentiels et ne seront utilisés que pour vous contacter dans le cadre de ce sondage.

51 Si vous nous permettez d'entrer en contact avec vous dans le cadre de ce sondage, nous vous prions de bien nous laisser votre adresse courriel.

Veuillez noter que votre adresse courriel restera confidentielle et ne sera utilisée que pour vous contacter dans le cadre de ce sondage.

52 Quel est votre poste principal actuel?

53 En quel(s) domaine(s) avez-vous effectué la plupart de votre formation professionnelle?

Par exemple, génie civil, géologie, etc.

54 Merci beaucoup pour vos réponses! Après les avoir analysées, nous aimerions vous proposer d'évaluer deux à deux les géotypes. Cela nous permettrait de mieux cerner les différences générales entre les géotypes que vous avez classés dans les mêmes groupes. Est-ce que vous nous autorisez à vous contacter pour participer à la deuxième phase? *

- Oui
- Non

Envoyer

Appendix 3.3.2. Pairwise comparison for experts in Dakar

The following questionnaire was submitted to the same nine experts recruited for the previous questionnaire (Appendix 3.3.1) and constituted a second phase. Again, only two responses were received, this time from the same professor or geomorphology and a professor of geology who did not participate in the first phase.

Quel est le potentiel d'utilisation et de valorisation de la géologie de Dakar?

C'est une question qui dépend de l'expérience des scientifiques et de praticiens comme vous qui savez comment en réalité (sur le terrain) se comportent les formations géologiques.

Pour ce faire, le projet Deep City à l'EPFL a adopté une méthode qui permet de situer chaque famille de formations géologiques sur une échelle relative d'aptitude. Vos réponses nous permettront de produire des cartes de potentiel que nous partagerons avec vous et avec des urbanistes de la ville de Dakar.

Démarrer

Comme pour la phase une, nous avons regroupé les formations géologiques en dix familles que nous nommons des *géotypes*:

Géotypes	Formations géologiques
APA – Alluvions des plaines	Fz (argile, sable et cailloutis) CF (sable argileux)
EOL – Sables dunaires	Sables rubéfiés (Dv-y), dunes blanches (Dlz4) et dunes jaunes (Dlz3)
GR – Grès	Grès calcaire coquillier (My)
LS – Sables littoraux	Sable coquillier (Sgz), des plages (Mz2-4) et des cordons littoraux
P – Dépôts palustres	Sables humifères (FTz, Tz)
LAV – Laves	Coulées de hawaiite (d5ß, m5ß, scn5ß), de basanite (4ß, 3ß)
M – Marne	Argiles et marnes (e4a, e2b, e1-3a)
MC – Alternance de Calcaires et de Marne	Alternances de marno-calcaires (e5b, e5c, e4b5, e4b1-4)
CA – Calcaire Argileux	Calcaires coquillers et marnes (e1) ; Calcaires argileux, marno-calcaires
PYR – Roches pyroclastiques	Tufs volcanites (5tf, scr5tf, 3tf, 2tf)

L'exercice que vous ferez ici est une comparaison par pairs. C'est une méthode testée scientifiquement qui nous permet de situer des alternatives sur une échelle relative d'importance, et cela dans une situation d'incertitude. L'incertitude ici relève surtout de l'échelle à laquelle nous étudions la géologie de Dakar.

La première phase a divisé chacun des géotypes en quatre groupes. Donc, nous évaluerons seulement ceux auxquels vous avez donné la même appréciation. Cela nous permet de réduire considérablement les comparaisons et ainsi d'économiser votre temps!

Nous vous poserons des questions sur le potentiel d'utilisation des géotypes pour trois ressources: l'espace, les géomatériaux et l'eau souterraine. Si une de ces ressources se trouvent en dehors de vos compétences, nous vous prions de bien vouloir passer à la comparaison suivante.

Cette première partie sollicite votre appréciation du potentiel des géotypes pour la construction d'espace souterrain.

Une boîte de texte se trouve à la fin de cette section pour toutes commentaires que vous avez à propos de votre appréciation.

1 Toute chose étant égale par ailleurs, lequel des deux géotypes est préférable pour la construction souterraine?

a. Les grès (GR) ou les laves (LAV)?

GR : grès calcaire coquillier (My)
LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)

Grès (GR) Laves (LAV)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

3 Toute chose étant égale par ailleurs, lequel des deux géotypes est préférable pour la construction souterraine?

a. Les marno-calcaires (MC) ou les roches pyroclastiques (PYR)?

MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)
PYR : tufs volcanites (5tf, scr5tf, 3tf, 2tf)

Marno-calcaires (MC) Roches pyroclastiques (PYR)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

5 Toute chose étant égale par ailleurs, lequel des deux géotypes est préférable pour la construction souterraine?

a. Les marnes (M) ou les calcaires argileux (CA)?

M : argiles et marnes (e4a, e2b, e1-3a)
CA : calcaires coquilliers et marnes (e1)

- Marnes (M)
- Calcaires argileux (CA)

À quel degré les sont-ils/elles préférables?

0	1	2	3	4	5	6	7	8	9

Peu préférable (les deux sont presque égaux) — Très préférable

---

7 Avez-vous des commentaires à nous communiquer à propos de votre évaluation?

Sinon, appuyer sur "Entrée"

Maintenant nous nous intéressons à votre appréciation du potentiel des géotypes pour un autre usage: les géomatériaux--c'est-à-dire leur potentiel à être valorisé sur ou hors-site dans le remblai, les agrégats ou autre.

Une boîte de texte se trouve à la fin de cette section pour toutes commentaires que vous avez à propos de votre appréciation.

---

8 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les grès (GR) ou les sables littoraux (LS)?

GR: grès calcaire coquillier (My)

LS: sable coquillier (Sgz), des plages (Mz2-4), et des cordons littoraux

- Grès (GR)
- Sables littoraux (LS)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

10 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les laves (LAV) ou les marnes (M)?

LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)
M : Argiles et marnes (e4a, e2b, e1-3a)

- Laves (LAV)
- Marnes (M)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

12 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les alluvions des plaines (APA) ou les grès (GR)?

APA : argile, sable et cailloutis (Fz) et sable argileux (CF)
GR : grès calcaire coquillier (My)

- Alluvions des plaines (APA)
- Grès (GR)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

14 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les laves (LAV) ou les calcaires argileux (CA)?

LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)
CA : calcaires coquilliers et marnes (e1)

- Laves (LAV)
- Calcaires argileux (CA)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

16 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les alluvions des plaines (APA) ou les sables littoraux (LS)

APA : argile, sable et cailloutis (Fz) et sable argileux (CF)
LS : sable coquillier (Sgz), des plages (Mz2-4), et des cordons littoraux

- Alluvions des plaines (APA)
- Sables littoraux (LS)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

18 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les sables dunaires (EOL) ou les laves (LAV)?

EOL : sables rubéifiés (Dv-y), dunes blanches (Dlz4) et jaunes (Dlz3)
LAV : coulées de hawaiite (d5ß, m5ß, scn5ß) et de basanite (4ß, 3ß)

- Sables dunaires (EOL)
- Laves (LAV)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

20 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les sables littoraux (LS) ou les marno-calcaires (MC)

LS : sable coquillier (Sgz), des plages (Mz2-4), et des cordons littoraux
MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)

- Sables littoraux (LS)
- Marno-calcaires (MC)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

22 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les sables dunaires (EOL) ou les marnes (M)?

EOL : sables rubéifiés (Dv-y), dunes blanches (Dlz4) et jaunes (Dlz3)
M : argiles et marnes (e4a, e2b, e1-3a)

- Sables dunaires (EOL)
- Marnes (M)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

24 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les grès (GR) ou les marno-calcaires (MC)?

GR : grès calcaire coquillier (My)
MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)

- Grès (GR)
- Marno-calcaires (MC)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

26 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les sables dunaires (EOL) ou les calcaires argileux (CA)?

EOL : sables rubéifiés (Dv-y), dunes blanches (Dlz4) et jaunes (Dlz3)
CA : calcaires coquilliers et marnes (e1)

- Sables dunaires (EOL)
- Calcaires argileux (CA)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

---

28 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

a. Les marnes (M) ou les calcaires argileux (CA)?

M : argiles et marnes (e4a, e2b, e1-3a)
CA : calcaires coquilliers et marnes (e1)

- Marnes (M)
- Calcaires argileux (CA)

À quel degré les sont-ils/elles préférables?

0 1 2 3 4 5 6 7 8 9

Peu préférable (les deux sont presque égaux) Très préférable

30 Toute chose étant égale par ailleurs, lequel des deux géotypes est plus intéressant comme géomatériaux pour une valorisation sur ou hors site?

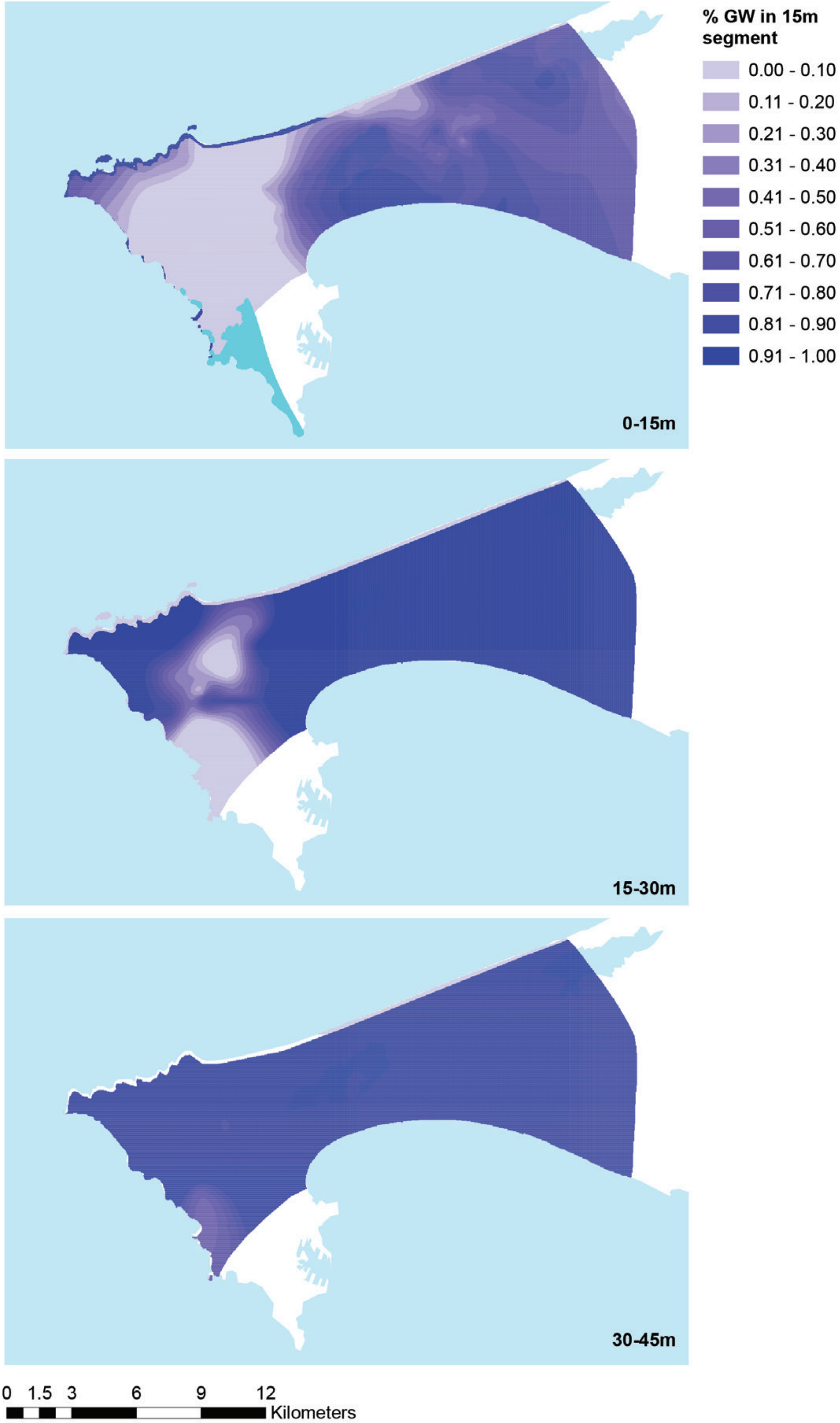
a. Les alluvions des plaines (APA) ou les marno-calcaires (MC)?

APA : argile, sable et cailloutis (Fz) et sable argileux (CF)
MC : alternances de marno-calcaires (e5b, e5c, e4b5, e4b1, e4b1-4)

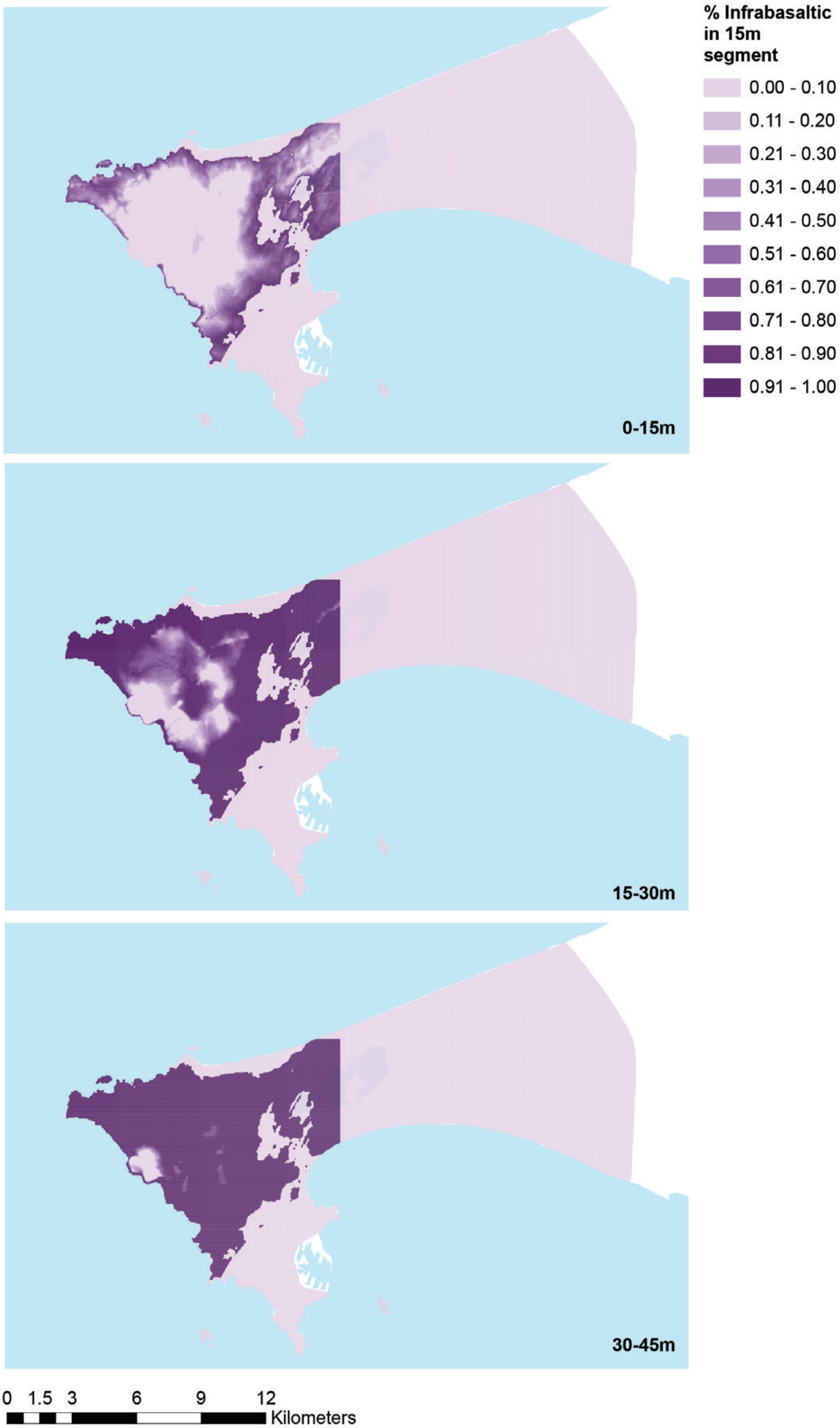
- Alluvions des plaines (APA)
- Marno-calcaires (MC)

Envoyer

Appendix 3.3.3. Percent of Groundwater at 0-15, 15-30, 30-45 m deep.



Appendix 3.3.4. Percent of infrabasaltic sands aquifer at 0-15, 15-30 and 30-45 m deep.



Appendix 3.3.3. Sample of Python Code for Aggregation of Criteria for the Constructability Potential.

```
#Import necessary modules
import arcpy
from arcpy.sa import *

#Identify the feature class to work in and the list of fields
feature_class = r’Z:\Dakar\Dakar.gdb\Grids\Dakar_25x25Grid’
print “Feature classes identified successfully”

cursor = arcpy.UpdateCursor(feature_class, where_clause=”Elevation IS NOT NULL”)
#cursor = arcpy.UpdateCursor(feature_class)
print “Cursor defined successfully”

#Define the criteria weights (often calculated using AHP)
CW_01 = 0.2000
CW_02 = 0.2000
CW_03 = 0.2000
CW_04 = 0.2000
CW_05 = 0.2000

print “Criteria weights successfully defined”

#Define the Order weights for the best case scenario (OR, i.e. where we capitalize on the strengths of the site)
#Here, we use alpha of 0.3
OWOR_1 = 0.3962
OWOR_2 = 0.2574
OWOR_3 = 0.1672
OWOR_4 = 0.1086
OWOR_5 = 0.0706

#Define the Order weights for the worst case scenario (AND, i.e. where we rate highly the weaker aspects of the site)
#Here, we use alpha of 0.7
OWAND_1 = 0.0706
OWAND_2 = 0.1086
```

```
OWAND_3 = 0.1672
OWAND_4 = 0.2574
OWAND_5 = 0.3962

#Define the Order weights for the standard AHP (0.5 level of Orness)
OWAHP_1 = 0.2000
OWAHP_2 = 0.2000
OWAHP_3 = 0.2000
OWAHP_4 = 0.2000
OWAHP_5 = 0.2000

print "Order weights successfully defined"

#Calculate the OWA score based on a reordering of the normalized criterion values
print "Beginning OWA score calculation..."
for row in cursor:
    #Calculate the normalized criterion values.
    CV_01 = row.va_SpPot15
    CV_02 = row.va_UrbPot
    CV_03 = row.min_GWSat15
    CV_04 = row.min_PcIB15
    CV_05 = row.Elevation
    CV_list = [CV_01, CV_02, CV_03, CV_04, CV_05]
    #Here, we need to create a second list which is the normalized criterion value, the ordering of which determines the order of the criteria weights.
    CW_list = [CW_01, CW_02, CW_03, CW_04, CW_05]
    CV_list_sorted, CW_list_sorted = zip(*sorted(zip(CV_list, CW_list), reverse=True))
    #Calculate, write out and iterate the OWA scores.
    SpPot15_03_lu = CW_list_sorted[0]*OWOR_1+CW_list_sorted[1]*OWOR_2+CW_list_sorted[2]*OWOR_3+CW_list_sorted[3]*OWOR_4+CW_list_sorted[4]*OWOR_5
    row.SpPot15_03 = (CV_list_sorted[0]*CW_list_sorted[0]*OWOR_1+CV_list_sorted[1]*CW_list_sorted[1]*OWOR_2+CV_list_sorted[2]*CW_list_sorted[2]*OWOR_3+CV_list_sorted[3]*CW_list_sorted[3]*OWOR_4+CV_list_sorted[4]*CW_list_sorted[4]*OWOR_5)/SpPot15_03_lu
    SpPot15_07_lu = CW_list_sorted[0]*OWAND_1+CW_list_sorted[1]*OWAND_2+CW_list_sorted[2]*OWAND_3+CW_list_sorted[3]*OWAND_4+CW_list_sorted[4]*OWAND_5
    row.SpPot15_07 = (CV_list_sorted[0]*CW_list_sorted[0]*OWAND_1+CV_list_sorted[1]*CW_list_sorted[1]*OWAND_2+CV_list_sorted[2]*CW_list_sorted[2]*OWAND_3+CV_list_sorted[3]*CW_list_sorted[3]*OWAND_4+CV_list_sorted[4]*CW_list_sorted[4]*OWAND_5)/SpPot15_07_lu
```

```
    SpPot15_05_lu = CW_list_sorted[0]*OWAHP_1+CW_list_sorted[1]*OWAHP_2+CW_list_sorted[2]*OWAHP_3+CW_list_sorted[3]*OWAHP_4+CW_list_sorted[4]*OWAHP_5
    row.SpPot15_05 = (CV_list_sorted[0]*CW_list_sorted[0]*OWAHP_1+CV_list_sorted[1]*CW_list_sorted[1]*OWAHP_2+CV_list_sorted[2]*CW_list_sorted[2]*OWAHP_3+CV_list_sorted[3]*CW_list_sorted[3]*OWAHP_4+CV_list_sorted[4]*CW_list_sorted[4]*OWAHP_5)/SpPot15_05_lu
    cursor.updateRow(row)

#It may be worth eventually having the results print the normalized values (and some additional statistics on the calculation).
print “Completed Successfully for Dakar’s Spatial Potential at 0-15m.”
```

Curriculum Vitæ

CURRICULUM VITÆ

Michael Robert Doyle

PhD candidate in Architecture and the Sciences of the City
Laboratory of Environmental and Urban Economics (LEURE)
Deep City Project
École polytechnique fédérale de Lausanne (EPFL)
Lausanne, Switzerland

MICHAEL ROBERT DOYLE

PhD Candidate in Architecture and the Sciences of the City
Laboratory of Environmental and Urban Economics (LEURE)
Deep City Project
École polytechnique fédérale de Lausanne
Lausanne, Switzerland; 1015
Telephone: +41 (0)21 693 93 99

Email: michael.doyle@epfl.ch

Birth date: October 15, 1982

Languages:
English, French (Reading, speaking and writing fluency, C2)
Spanish (Elementary reading comprehension, A1)
German (Intermediate conversation and reading comprehension, B1)
Mandarin, Swedish (Notions, A0)

DIPLOMAS:

2011	M. Sc.	Architecture, Université Laval, Quebec, Canada Thesis title: Designing for mobile activities: WiFi hotspots and users in Quebec City
2010	M. Arch.	Architecture, Université Laval, Québec, Canada
2005	B. Sc. Arch.	Architecture, University of Cincinnati, Ohio, United States

ADDITIONAL EDUCATION

2006
Inlingua Language Center, Chicago, Illinois (United States)
Private Mandarin course
8 weeks (2 hrs/week)

2004
Écoles d'art américaines de Fontainebleau, Fontainebleau (France)
Summer architecture program
6 weeks

PROFESSIONAL EXPERIENCE

July 2012-Present

Doctoral Assistant
Laboratory of Environmental and Urban Economics (LEURE)
Institute of Architecture and the City (IA)
École polytechnique fédérale de Lausanne (EPFL), Switzerland
Principal responsibilities: conducting independent research activities towards a PhD in architecture and the sciences of the city; carrying out field work with collaborators in Switzerland, Asia or elsewhere; occasional teaching and organization of courses given with thesis advisor, as well as participation in architectural juries or the supervision of Master's level architecture students.

Jan 2011- Jun 2012

Research Professional
Interdisciplinary Research Group on the Suburbs (GIRBa)
Research Centre for Regional and Territorial Development (CRAD)
Université Laval (Canada)
Principal responsibilities: Development and programming (using Sawtooth CiW) of questionnaire and production of promotional material for an Internet survey conducted for the metropolitan region of Quebec City as part of a team of one professor, one professional researcher and three students. Presentations to local decision-makers.

2010-2011

Operations Coordinator
School of Architecture, Université Laval
Principal responsibilities: Coordination of 2010-2011 architecture conference series, monthly round-table debates and an international architecture competition; Planning of 50th anniversary alumni reunion.

2008-2010

Research Assistant
Interdisciplinary Research Group on the Suburbs (GIRBa)
Research Centre for Regional and Territorial Development (CRAD)
Université Laval (Canada)
Principal responsibilities: various levels of contribution to an FQRSC, provincially-funded, research project "*De l'étalement à la dispersion: Comprendre les mutations de l'urbain et agir pour des collectivités viables"*; aid in organizing knowledge-transfer seminars and French-English translation of scientific articles for publication.

2008

Research Assistant
Canada Research Chair on Built Religious Heritage
School of Architecture, Université Laval (Canada)
Principal responsibilities: participation in a nationally-funded research project, specifically comprising the reconstruction of the evolution of properties owned by religious communities in Québec City through consultation of visual and written archival documentation.

2005-2007

Architecture intern (pre-licensing in North America), Computer rendering artist Daniel P. Coffey & Associates, Chicago, Illinois (United States)
Principal responsibilities: production of 3D renderings for project conception and presentation to clients. Coordinated and trained a team of four individuals in the principles of lighting and modeling using Autodesk 3D

	Studio Max, VRAY render engine and Adobe After Effects CS3 for 3D animations
2004 (Autumn)	La S.C.A.U., Paris (France) Principal responsibilities: development of construction drawings using Autodesk AutoCAD and renderings using AutoCAD and Adobe Photoshop for the renovation of the headquarters of IT giant CÉGID Groupe; produced schematic drawings for competition boards of a hospital project; provided occasional French-English translation for firm communications.
2004 (Autumn)	Agence Tom Sheehan, Paris (France) Principal responsibilities: developed a 3D model and renderings for a gymnasium competition in Cavalaire-sur-mer, near Marseille; produced section drawings of a housing complex for the French national police force (La Gendarmerie).

AWARDS AND ACADEMIC DISTINCTIONS

January 2013	Prize for the Best Essay on Urban and Regional Themes by Young Authors. Overall winner for 2012 of the competition for paper entitled "Designing for Mobile Activities. WiFi Hotspots and Users as Inspiration for the Creative Programming of Place". Award of £1000.
May 2012	VRM (Villes-régions-monde) Prize for the Best Dissertation or Thesis in Urban Studies, 2012 recipient shared with one other candidate.
May 2010	2010 Université Laval Recipient of the Royal Architectural Institute of Canada Student Medal Induction into the Royal Architectural Institute of Canada Student Honour Roll Recognition for best grade point average of graduating double Masters students. Award “Remarkable integration of new into existing context” for capstone M. Arch. project Nominated for the Bourse du Collège des Présidents offered by the Ordre des architectes du Québec (OAQ).
June 2005	DAAPWorks Honor Award for capstone B. sc. Arch. Project (University of Cincinnati)
July 2004	Prix exceptionnel du château de Fontainebleau for originality of projects produced during the 6 week architecture summer school.

TECHNICAL SKILLS

Operating Systems	Microsoft Windows 98SE – 7 Mac OS 9 et OS X Linux (notions)
Graphic Layout	Adobe Creative Suite (Photoshop, Illustrator, InDesign, Acrobat) Adobe After Effects CS3

Web Software	Macromedia Dreamweaver MX Macromedia Flash MX
CAD and 3D Modeling	Autodesk AutoCAD (FR & EN) Autodesys Form Z (notions) Autodesk 3DS Max 8 ChaosGroup Vray 1.46 (rendering engine)
Geographic information systems (GIS)	QGIS, ArcGIS (also, Network Analyst)
Web Survey Software	Sawtooth CiW (Web interviewing)
Qualitative analysis	QDA Miner TAMS Analyzer
Quantitative analysis	SPSS 18.0

RESEARCH ACTIVITIES

As principal researcher

Working title — *Potentialities of the Urban Volume: Mapping underground resource potential and deciphering spatial economies and configurations of multi-level urban spaces*

2012-2017 — Dissertation for satisfaction of a PhD in Architecture and the Sciences of the City
Main researcher: Michael Doyle
Research advisors: Aurèle Parriaux, professor emeritus of Geology, EPFL; Philippe Thalmann, professor of Economics, EPFL
$200,000

Project Title — *Designing for mobile activities: WiFi hotspots and users in Quebec City*

2008-2010 — Master of science in Architecture research project (M.sc.)
Main researcher: Michael Doyle
Research advisor: Carole Després, professor of architecture, Université Laval
Financing: bursary granted by the Interdisciplinary research group on the suburbs (GIRBa) as part of a provincially-funded project, FQRSC 2005-2009 (see below)
$15,000

Participation in other research projects

Project title — *Québec 2020: vers un projet collectif d’aménagement durable*

2010-2014 — FQRSC-soutien aux équipes seniors
Main researcher: Carole Després; Associate Researches: Manon Bouliane, Andrée Fortin, Pierre Gauthier, Florent Joerin, Nik Luka, Tania Martin, GianPiero Moretti, Stéphane Roche and Geneviève Vachon.
Position held: Professional researcher.
$460,000

Project title — *De l’étalement à la dispersion : Comprendre les mutations de l’urbain et agir pour* *des collectivités viables.*

2005-2009 FQRSC-support to research teams

Main researcher: Carole Després ; Associate researchers: Andrée Fortin, Florent Joérin, GianPiero Moretti and Geneviève Vachon

Position: Research assistant

$401,000

Project title *Étalement urbain et repli domestique*

2004-2007 SSHRC-grant

Main researcher: Andrée Fortin ; Associate researcher: Carole Després

Position: Research assistant

$135,000

PUBLICATIONS

Doyle, R. M.; Thalmann, P.; Parriaux, A. Underground Potential for Urban Sustainability: Mapping Resources and Their Interactions with the Deep City Method. *Sustainability* 2016, *8*.

Doyle, M. (2016). From Hydro/Geology to the Streetscape: Evaluating Urban Underground Resource Potential. *Tunnelling and Underground Space Technology*, *55*, 83.95. http://doi.org/10.1016/j.tust.2016.01.021

Doyle, M. (2015). Editorial: What do we *touch* when we visualize data? *Contour, Visual(izing) Data*. Online: http://contour.epfl.ch/en/what-do-we-touch-when-we-visualize-data/.

Doyle, M. (2014). Designing for Mobile Activities: WiFi Hotspots, Users and the Relational Programming of Place. In Sheller, M. & De Souza e Silva, A. (Eds.) Mobility and Locative Media: Mobile Technology in Hybrid Spaces. Routledge.

Thalmann, P. and M. Doyle. (2013). À la recherche de la densité optimale. In Rey, E. (Ed.) Green Density. Presses polytechniques universitaires romandes: Lausanne, Switzerland.

SCIENTIFIC COMMUNICATIONS

International (as main presenter unless indicated otherwise)

“From Hydrogeology to the Streetscape : Evaluating Urban Underground Resource Potential”. *25th Seminar on Urban Hydrogeology*. 3-4 février 2016. Trondheim (Norway).

“Volumetric Moments of the Horizontal : Where is the Potential in Dispersion?”, The Horizontal Metropolis. A Radical Project. VII International PhD Seminar ‘Urbanism & Urbanization’. 12-14 octobre 2015. EPFL (Suisse).

“Quel avenir pour le sous-sol urbain? Potentials du sous-sol et de la surface à San Antonio (Texas)”, Congrès international de l’Association française des tunnels et de l’espace souterrain (AFTES). October 13-15, 2014. Lyon (France).

“Breaking Vertical Boundaries: the spatial logics and underground potential of San Antonio, Texas”, 44th Annual Meeting of the Urban Affairs Association, March 19-22 2014. San Antonio (Texas, USA).

“Towards the Layered City: Redefining the Role of Underground Resources in Future Urbanization”, poster presented at the 2nd Delft International Conference on Complexity, Cognition, Urban Planning and Design, October 10-12 2013. Delft (The Netherlands).

“What future for the urban underground? A review of the literature on the planning and design of subsurface spaces”, Urbanism and Urbanization 6th International PhD Seminar, October 3-5 2014, Paris (France).

"Planning the vertical city: coordinating surface and subsurface organization", World Tunnelling Conference: Urban Problems – Underground Solutions Working Group, June 2 2013, Geneva (Switzerland).

Després, C., Doyle, M. "Designing for mobile activities: WiFi hotspots and users in Quebec City". Internatioinal Association for Person-Environment Studies (IAPS), 24-29 June 2012, Glasgow, Scotland (UK), [presented by C. Després]

Després, C., Vachon, G., Doyle, M., Rioux, J., Larouche-Laliberté, E., Michaud-Beaudry, R. "Which future for metropolitan areas? Using ICT to inform, consult and aid in decision-making". International Association for Person-Environment Studies (IAPS), 24-29 June 2012, Glasgow, Scotland (UK). [presented by C. Després]

"Designing for mobile activities: WiFi hostpots and users in Quebec City", Local and Mobile: linking mobilities mobile communication and locative media, March 16-18 2012, Raleigh, North Carolina (USA). Communication selected for publication in an edited volume.

"Designing for mobile activities: WiFi hotspots and users in Quebec City", Environmental Design Research Association annual colloquium, May 25-28 2011, Chicago, Illinois (USA).

Després, C., Belhaj-Messaoud, M., Doyle, M., Guindon-Bronsard, V., Ponsart, C. (2011) "Which Future for Metropolitan Areas? Understanding the Role of Territorial Representations in the Adhesion to a Collective Sustainable Project" Environmental Design Research Association annual colloquium, May 25-28 2011, Chicago, Illinois (USA). [presented with Després, C.]

"Work and Leisure in the Information Age: The role of public and semi-public places for Québec City WiFi users", Workshop "Housing and Spatial Studies", European Network for Housing Research, New Housing Researchers' Colloquium, 2-3 July 2010, Istanbul Technical University. Istanbul (Turkey). [nominated for best student paper]

"Work and Leisure in the Information Age: The role of public and semi-public places for Québec City WiFi users", Colloquium "Young Researchers' Workshop", International Association for Person-Environment Studies (IAPS), 26-27 June 2010, Helmholz Centre for Environmental Research, Leipzig (Germany).

"Travailler et se divertir avec les technologies mobiles (NTIC): les lieux publics et semi-publics et les utilisateurs WiFi à Québec", 7e colloque de la relève Villes-Régions-Mondes (VRM), 19 May 2010, Institut national de la recherche scientifique (INRS – UCS Montréal), Montréal (Canada).

"Understanding the Complementarities of Information and Communication Technologies and Geographic Travel in Emerging Mobilities: Mobile Teleworkers in Québec City", Poster Session, 4th Specialist Meeting of the Network ICTs, "Mobilizing Persons, Places and Spaces", 7-9 October 2009, Île d'Orléans, Québec, (Canada).

"Understanding the Impact of Mobile Communications Technologies on Individual Physical and Virtual Movement: A Review of the Literature", Colloquium "Communicative Cities: Integrating Technology and Place", The Urban Communication Foundation, 25-26 June 2009, Columbus, Ohio (USA).

Institutional and/or Public

"Quel avenir pour le sous-sol urbain? Potentiels du développement volumique à San Antonio (Texas, USA)". Presentation given during a workshop organized by the Deep City project and the City of Lausanne for geologists working at the cantonal level of Switzerland. 5 June 2015. EPFL (Switzerland).

"Deep City – de la conception à la pratique". Joint presentation with Pascal Blunier at "Planification stratégique du sous-sol" organized by the Swiss engineering firm CSD Ingénieurs for their clients and the public. 5 November 2015. Lausanne (Switzerland).

"Making, Mattering, Mapping. Constituting Underground Potential for Future Urban Development". International PhD colloquium: Research Methodologies for the Intercultural Dimensions of Territory. Organized by the inter-institutional urban lab network (Laboratory Basel, KRVIA Mumbai, Calabria Italy, TU Berlin). 14 November 2014. EPFL, Lausanne (Switzerland).

"Travailler et se divertir avec les technologies mobiles (NTIC): les lieux publics et semi-publics et les utilisateurs du WiFi à Québec", 15e colloque étudiant interdisciplinaire du Centre de Recherche en Aménagement et en Développement (CRAD), 12 March 2010, Musée de la civilisation, Québec (Canada).

"Travailler et se divertir avec les technologies mobiles (NTIC): les nouveaux rôles des lieux publics et semi-publics pour les utilisateurs du WiFi à Québec", presentation as part of the course "Séminaire de recherche II", 16 December 2009, School of Architecture, Université Laval, Québec (Canada).

INVOLVEMENT IN THEORETICAL COURSES

Swiss Federal Institute of Technology, Zurich (ETH)

May 2 2016 — Course title: A Quantum City
Instructors: Diana Alvarez-Marin, Miro Roman
Role: Lectured and lead a discussion on the philosophical questions posed by quantum physics and their importance for urban theory and the study of urban form.

School of the Natural, Architectural and Built Environment, Swiss Federal Institute of Technology, Lausanne, Switzerland

MOOC 2016 — MOOC title: Économie du sol et de l'immobilier (Land and Real Estate Economics)
Professor: Philippe Thalmann
Role: Recording of a module on spatial economics and urban models of the city. Available on Coursera.org.

April 25 – 29 2016 — ENAC Week: Le montage de projets de construction [Assembling a Construction Project]
Professors: Philippe Thalmann, François Golay
Role: Assisted in the organization of the course and gave a lecture to third year bachelor students in architecture, civil and environmental engineering on architectural programming and on the use of GIS in analysing the project's context.

April 27 – May 1 2015 — ENAC Week: Le montage de projets de construction [Assembling a Construction Project]
Professors: Philippe Thalmann, François Golay, Jacques Dubé
Role: Assisted in the organization of the course and gave a lecture to third year bachelor students in architecture, civil and environmental engineering on architectural programming and on the use of GIS in analysing the project's context.

March 11, 2015 — Course title: Foncier, Immobilier, Logement (Property, Real Estate, Housing)
Professor: Philippe Thalmann
Role: gave a lecture entitled "Indicateurs d'attractivité et la recherché de configurations spatiales 'idéales'" [Indicators of Attractiveness and the Search for 'Ideal' Spatial Configurations] on the construction of normative urban models from a spatial economic understanding of the organization of urban activities and the mathematical understandings of urban morphology and building form.

April 28 – May 2 2014 — ENAC Week: Le montage de projets de construction [Assembling a Construction Project]

Professors: Philippe Thalmann, François Golay, Jacques Dubé

Role: Assisted in the organization of the course and gave a lecture to third year bachelor students in architecture, civil and environmental engineering on architectural programming and on the use of GIS in analysing the project's context.

November 19, 2013 — Course title: Atelier d'architecture "Circle Lines"

Professor: Dieter Dietz

Role: worked with students on using graph theory and working with the results of an urban Network analysis of their semester projects. Theory and methods were presented as a lecture, followed by individual work with students.

Spring 2013 — Course title: Gestion du projet d'architecture [Architecture Project Management]

Professor Philippe Thalmann

Role: Produced a portion of the material and taught lessons on Swiss standards for calculating building dimensions and strategies to use them in evaluating design options, and on project scheduling methods and tools (Gantt, Precedence Diagrams, Staff Schedules). Corrector for exams.

Autumn 2012 — Course title: Gestion du projet d'architecture [Architecture Project Management]

Professor: Philippe Thalmann

Role: Produced the material for and taught a lesson on the theoretical and practical aspects of architectural programming. Proctor and corrector for exams.

School of Architecture, Université Laval, Québec

Autumn 2011 — Course title: Atelier de programmation architecturale et urbaine [Urban and Architectural Programming]

Professor/Instructor: Carole Després, Michael Doyle

Role: Co-instructor in a Master's level architecture and urban design studio; leading of student discussions and site visits; coordination studio activities and external partners; feedback during presentations by students to local decision-makers and experts.

Project: The revitalization of three Quebec City area secondary schools through the evaluation of existing site conditions at the urban and building scales, the review of recent literature, surveys conducted among school personnel, analysis of mental maps drawn by secondary students, analysis using Space Syntax and the investigation of innovative precedents in school architecture.

Autumn 2011 — Course title: Programmation et évaluation architecturales [Architectural Programming and Evaluation]

Professor: Carole Després

Role: Commentary of student presentations as guest critic; grading of student projects.

April 7, 2011 — Course title: Recension des écrits [Literature Review]

Professor: Nabila Bachiri

Role: presentation of the role of the literature review in a research project using my own Master's of science thesis as a case in point.

April 4, 2011	Course title: Forme urbaine et pratiques culturelles [Urban Form and Cultural Practices] Professor: Rémy Barbonne Presentation title: “La ville numérique: quel intérêt pour les architectes et urbanistes?”
March 24, 2010	Course title: Forme urbaine et pratiques culturelles Professor: Carole Després Role: guest critic.
January 21, 2010	Course title: Forme urbaine et pratiques culturelles Professor: Carole Després Presentation title: “Travailler et se divertir avec les technologies mobiles (NTIC): les lieux publics et semi-publics et les utilisateurs WiFi à Québec”
Winter 2009	Course title: Forme urbaine et pratiques culturelles Professor: Carole Després Role: Assistant in developing the group project for the second half of the course

St-Lawrence College, Québec

February 24, 2010	Course title: Québec Local Tour Guide
March 1, 2010	Professor: Stephen Marchessault
	Role: gave two 2.5 hour lessons on the history of the architecture of Quebec City.

PARTICIPATION IN ARCHITECTURAL JURIES

Master Project	Intermediate critiques for five Master’s students (Philippe Thalmann)	
AR-312	Figuration et représentation de l’architecture (Nicola Braghieri)	W15
ARC-1007	Habitabilité et poésie de l’espace (James Leeming)	W12
ARC-3106	Architecture et rapport Homme/Nature/Société (Philippe Barrière)	W10
ARC-2005	Atelier 4: Intégration et formalisation de concepts (Tania Martin)	W10
ARC-1007	Habitabilité et poésie de l’espace (James Leeming)	W10

ORGANIZATION OF ACADEMIC CONFERENCES

Agency/Agents of Urbanity. EPFL. 1-2 June 2015

International PhD colloquium co-organized with colleague Dario Negueruela del Castillo. Responsibilities included writing up and distributing the initial call for contributions, contacting and composing the international scientific committee and keynote speakers, drawing up a budget and acquiring the necessary funds. Currently organizing a follow-up call for contributions to edit a special edition of the review *Contour* on the themes addressed in the colloquium. Participants included students as far away as Australia and the US.

16e colloque étudiant interdisciplinaire du CRAD

Served on the first student-led organization committee for the annual interdisciplinary student colloquium held at Laval University. Collaborated with four other graduate and post-graduate students as well as the director of the research center in reviewing presentation proposals. Served on the selection jury for three prizes awarded to best presentations. Also produced all posters, announcements and the program.

PARTICIPATION ON COMMITTEES

January 2014 – present Editorial board and founding member of the doctoral scientific journal *Contour*; organization and promotion of the first call for contributions "What is Research in Architecture?" currently in its second round of peer review.

June 2013 – present PhD representative on the Architecture and Sciences of the City (EDAR) steering committee. One of two delegates responsible for communicating and coordinating the activities of the doctoral student body. Projects include the establishment of a student-run academic journal and of an institutional EDAR research fair.

Winter 2005 & Spring 2005 American Institute of Architecture Students (University of Cincinnati)

Served as president of the student organization, organizing notably a poetry slam benefiting tsunami victims.

Fall 2003 & Spring 2004 American Institute of Architecture Students (University of Cincinnati)

Served as treasurer for two trimesters, managing most notably a trip to Austin, Texas for the annual AIAS forum.

RADIO INTERVIEWS

Invited by Claude Bernatchez, host of *Première Heure* on the radio of Radio-Canada, to discuss my Master of science in architecture (M. Sc.) research project, March 22, 2010.

TELEVISION INTERVIEWS

Interview with Dina Desmarais, journalist of the show *Planète* on Canal Savoir, discussing the impact of WiFi on public and semi-public places, December 1st 2009.

NEWSPAPER ARTICLES

Larose, Y. « Québec, ville Wi-Fi » Au Fil des Événements [journal universitaire]. 47 (28) 19 April 2012

Porter, Isabelle. « Réinventer la ville – Le Wi-Fi, c'est branché » Le Devoir [journal provincial]. 1 August 2012