



# Mapping urban underground potential in Dakar, Senegal: From the analytic hierarchy process to self-organizing maps

Michael R. Doyle\*

*Deep City Project, Laboratory for Environmental and Urban Economics (LEURE), École polytechnique fédérale de Lausanne (EPFL), Switzerland*

Received 27 June 2018; accepted 30 April 2019

## Abstract

This article presents a mapping method that seeks to provide urban planning with a diagnostic overview of the underground resources of an urban area. Resource potentials (for buildable space, groundwater or geomaterial extraction and geothermal energy) tend to be investigated on a needs-only basis once a project or plan has already been elaborated. This paradigm of ‘needs to resources’ risks favoring single-use rather than multi-use underground development, leading to unforeseen conflicts between possible uses (e.g., pollution of an aquifer or congestion of infrastructure) or the irreversible loss of potential synergies (e.g., geothermal collectors on building foundations). The Deep City project at the EPFL in Switzerland has been working on an alternative paradigm of ‘resources to needs’, which is a holistic approach addressing the underground as a source of opportunity in synergy with surface development for curtailing urban sprawl while preserving public places or parks. The method, which combines geological and surface urban data, produces maps of individual and combined resource potentials without prioritizing any particular planning objective. This communication will present the method and the resulting maps through a case study conducted in 2016 in the city of Dakar, Senegal. After first summarizing the Deep City project and the mapping method, the urban and geological conditions of Dakar will be presented, followed by the application and results of the Deep City method. The calculation of the combined potentials map is an opportunity to compare two alternative methods of combination, the Analytic Hierarchy Process and Self-Organizing Maps (SOM). Although the mapping method does not require complicated data collection or analysis, the SOM may be better suited both for dealing with larger quantities of data and for providing more meaningful mappings of geological and urban data in three dimensions.

© 2019 Tongji University and Tongji University Press. Production and hosting by Elsevier B.V. on behalf of Owner. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

*Keywords:* Urban planning; Geographical information systems; Geomaterials; Groundwater; Geothermal; Underground space

## 1 Introduction: an alternate paradigm for planning underground resources

### 1.1 Towards a paradigm of ‘resources to needs’

The geological conditions of the urban underground tend to be addressed as an afterthought in urban planning and are oriented towards single-function infrastructures.

This lack of a holistic approach in the planning phase and of a monofunctionality in application has proven problematic. For instance, groundwater extraction in the regions of Mexico and Paris has led to subsidence in both cities (Blunier, 2009; Ortiz-Zamora & Ortega-Guerrero, 2010). Following the moratorium placed by the French capital on pumping for industrial reasons, the groundwater table rose and flooded basements. The gradual increase in metro lines and underground spaces and infrastructure makes it difficult for cities to add additional infrastructure or link existing ones. Although cities such as Toronto and Montreal are cited as exemplary for the successful integra-

\* Address: Research Group for Architecture Theory and Philosophy of Technics (ATTP), TU Wien, Austria.

E-mail address: [michael.doyle@attp.tuwien.ac.at](mailto:michael.doyle@attp.tuwien.ac.at)

<https://doi.org/10.1016/j.undsp.2019.04.004>

2467-9674/© 2019 Tongji University and Tongji University Press. Production and hosting by Elsevier B.V. on behalf of Owner. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

tion of underground spaces into their urban fabric (Bélanger, 2007; Boisvert, 2011; El-Geneidy, Kastelberger, & Abdelhamid, 2011), their emergence has been facilitated by unique geological and hydrogeological conditions, making their model difficult to export elsewhere without accounting for the geological (and urban) heterogeneity of each city.

The urban planning process tends to investigate the underground conditions of a city on a needs-only basis and to rarely consult geological maps or sections during the early planning stages. The geology of an urban area may be suitable not only for underground construction but also for passive heating and cooling systems using geothermal, the local extraction of groundwater for irrigation and flood control and the use of extracted geomaterials on or off site. As part of a drive towards sustainability, the underground can assist in increasing urban density without building upwards while also protecting open and green spaces on the surface (International Tunnelling and Underground Space Association, 2012). The Deep City project at the EPFL in Switzerland has, since 2005, been reviewing existing scientific literature and strategies for application in order to develop a mapping method for providing the planning process with an overview of an urban area's multi-resource underground potential (Parriaux, Blunier, Maire, Dekkil, & Tacher, 2010; Parriaux, Tacher, & Joliquin, 2004). In contrast to recent underground potential maps or methods produced by cities such as Helsinki (Vähäaho, 2016), Hong Kong (Wallace & Ng, 2016) and in mainland China (Zhao, Peng, Wang, Zhang, & Jiang, 2016), the Deep City method does not focus only on underground space potential but also on geothermal, groundwater and geomaterial potentials as well. These four resources, particularly where they overlap, are possible sources of both conflict and synergy for the future transformation of an urban area.

By producing maps that are not oriented toward a particular planning objective, the Deep City project hopes to encourage a reversal of the 'needs to resources' paradigm to one of 'resources to needs' in which necessity plays little to no role in the diagnostic process. This alternative paradigm questions the adequacy of considering that all innovative uses of the resource potentials have to be decided in advance and of mapping in order to simply identify the most adequate 'use' for an area. Such an approach precludes the opportunity for other solutions to emerge during the elaboration of urban plans or particular projects (Doyle, 2017). The mapping method has been refined and tested in cities such as Geneva (Blunier, 2009), Suzhou, China (Li, Parriaux, Thalmann, & Li, 2013), San Antonio, Texas (Doyle, 2016a, Chapter 3.1), Hong Kong, China and most recently in Dakar, Senegal (Doyle, 2016b, Chapters 3.2–3.3). With these last three, a spatial analysis of the geometry of the existing street network and buildings, distributions of activities or population was added to the method to account for the role of centrality in underground space potential. Dakar is an interesting case because not

only has no extensive research been done on urban underground potential in Africa, Dakar is also facing important population growth on a topography characterized by heterogeneous geological conditions and regular flooding as well as limited land for continued expansion. As a city with little to no existing underground construction, it has a unique opportunity to address its underground resources while avoiding the errors of European or North American cities. Furthermore, Dakar was a case where the Deep City project could most extensively explore the practical implications of the resources to needs paradigm, which poses a particular challenge for the legibility and interpretation of resulting visualizations.

This article will provide a demonstration of the Deep City method using the case of Dakar, Senegal. The objective is to discuss some of the questions and problems raised by the production of a method that seeks to be generic and applicable with some modifications to different contexts. For this reason, it is important to underline the fact that the mapping method itself does not seek to be normative, but purely descriptive. It works from available data, which may be incomplete, in order to give a descriptive overview of the resource potential of an urban area. By 'potential', we mean the properties of the ground itself as potential conflicts or synergies between resources. It is up to any urban area to decide what to do with these potentials with respect to their current economic or social conditions and with respect to local issues around land ownership. The normative step is one that should be taken with respect to the specific objectives, challenges and cultural inclinations of a city's population. The Deep City method neither seeks to shortcut local geological investigations by experts nor the deliberative planning process. There is no single correct model for a 'deep city'. Section 1.2 will briefly describe the method, referring the reader to other publications with more detail. Section 2 will introduce the case of Dakar and provide some context as to the relationship between its urban growth and its ground conditions. The following section will present the evaluation of Dakar's underground potential and raise questions for the city's planning objectives and masterplan. Section 4 then concludes the paper with a discussion on the methodological challenges of aggregating the four resource potentials into a single map and compares two approaches: one based on a classical decision-making aid, the Analytic Hierarchy Process, and an alternative approach based on the self-organizing map algorithm.

### *1.2 Deep city method: data to GIS to aggregation and indexing*

The Deep City method involves three main steps: (1) the collection and compilation of data into a spatial data set, (2) the intermediate evaluation of resource potentials by local experts, and (3) the transformation of the data into individual and combined potential maps. The spatial information dataset is compiled in a geographical information

system software using a common spatial unit that captures the smallest resolution of the data (e.g., a 25 by 25 or 50 by 50 metre grid). Using a common grid has the advantage of being able to account for different types of data collected at different scales. To simplify the geological descriptions for ease of communication between nongeologists and geologists, Parriaux and Turberg (2007) proposed a classification system by which geological formations are grouped into 'geotypes' according to their genealogy (geological era) and sedimentology (petrographic/mineral qualities).

As described in greater detail elsewhere (Doyle, 2016a, 2016b, Chapter 3.0) and demonstrated later in this article, the relative resource potentials of each geotype are quantified using the Analytic Hierarchy Process (Saaty, 1990), which is a multicriteria decision-making aid. Local geologists conduct pairwise comparisons of the geotypes for each resource (ease of construction, use of excavated materials, tendency to contain groundwater and geothermal potential) using a common comparison scale of 1–9 (per the reasoning described in Saaty, 1980). The individual scores for each comparison are averaged among the geologists and inserted into a matrix, the reduction of which results in a small set of vectors and a principal eigenvector. This has the advantage of situating the geotypes on a relative scale by which the distance between the values of the geotypes can be interpreted as a measure.

Other data can be incorporated into the model in order to better evaluate the underground potential, e.g., data on groundwater levels or aquifer systems, topography for identifying flood-prone areas or steep slopes. The current urban conditions are an essential source of information: Simulations by the Deep City project on construction costs of surface and subsurface alternatives for a commercial building in Switzerland found that feasibility depended not only on the geological conditions of the site but also the location in the city—underground commercial construction tends to be more attractive where land values are high and near captive clientele (Maire, 2011, Chapter 4). An econometric analysis of Montreal found that more centrally located and better connected surface and subsurface food and retail spaces commanded a higher rental value (Doyle, 2016b, Chapter 2). To calculate centrality, a spatial network model of building footprint and street centerline data is built in ArcGIS and then analyzed at various network radii using the Urban Network Analysis Toolbox (Sevtsuk & Mekonnen, 2012). Whereas the Deep City case studies of San Antonio and Hong Kong settled on a single metric and radius for centrality, the case of Dakar presented below ran analyses at multiple metrics and radii in order to capture the nested nature of urban centrality (Hillier, 2012). The underlying patterns of centrality are then identified using a principal component analysis.

Using the Analytic Hierarchy Process (AHP), the evaluation of geotype potential, data on groundwater and urban centrality can be compared pairwise and assigned a relative value using matrix algebra. This approach is suitable for

individual resource potentials where the comparisons are motivated by the relative importance of each criterion for a particular resource. The aggregation of the four resources proves challenging for the AHP, however, because the mapping process does not seek to give precedence to one resource potential over another, which is at odds with the AHP's need for a clear hierarchy in the criteria. This shortcoming will be addressed in the case of Dakar by testing an alternative method for establishing relationships between criteria: a slightly unorthodox—but highly promising—use of the self-organizing map (SOM) algorithm (Kohonen, 2001, 2015; Moosavi, 2017). Rather than aggregate the resource potentials with the AHP, the SOM indexes the underlying patterns of combined potentials. The advantages and disadvantages of this approach will be discussed in the conclusion.

## 2 Conditions: urbanization over a heterogeneous ground

Dakar, the capital city of Senegal, is situated on an isthmus extending into the Atlantic Ocean off the west coast of continental Africa (Fig. 1). European settlement, principally by the French, began in the seventeenth century on the island of Gorée and then progressively moved to the mainland with the founding of the city of Dakar in 1857 on the southern tip of Cap Vert, which is a volcanic landmass connected to the mainland by low-lying sand formations. From the nineteenth century into the early twentieth century, Dakar's political and economic importance increased with the connection of its port to the inner continent by rail and its election as capital of French West Africa (Sinou, 1990). The first masterplan (following an initial 19th century parcel plan, plan de lotissement) was drawn up in 1946 by a French colonial government interested in strengthening its military presence in West Africa following the Second World War. Major roads linked military installations from the southern tip at Cap Manuel to a former airport at Ouakam. Residential areas were scattered between industrial and commercial or administrative areas with Europeans living generally in separate settlements from the local Senegalese (Seck, 1970).

With the influx of population following the development of Dakar after the war and its independence from France in 1960, the initial masterplan was updated in 1967 (the Ecochard plan) and addressed the expansion of the urban area into the low-lying, humid, agricultural zones (locally referred to as niayes) on the isthmus (Seck, 1970). Facing an economic crisis, the government commissioned a private firm to produce the 1980 masterplan. However, the plan dealt more with the management of existing development than a proposal for an overall vision for the city. The next major masterplan, Dakar Horizon 2025, would not be drawn up until 2010, notably in response to the continued development in the flood-prone regions of the niayes (Cities Alliance Project, 2010). Although the plan proposed an overall vision based upon a polycentric settlement pattern linked by transport infrastructure, it was criticized

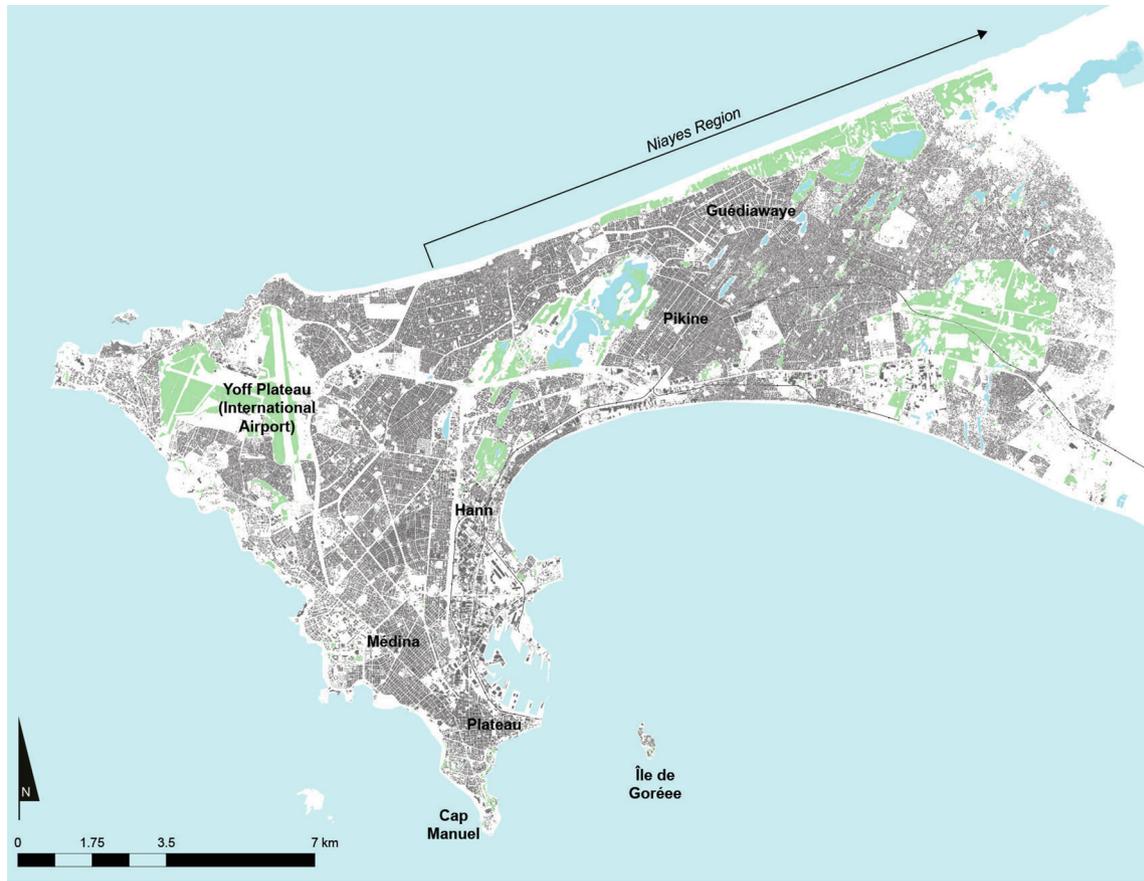


Fig. 1. The Cap-Vert peninsula with the Cap (from Cap Manuel to the Yoff Plateau) and the isthmus connecting the Cap to the continent (data sources: Open Street Map; ANAT, Dakar).

for not better integrating the needs of the local population into the planning process and for the inadequacy of its proposed management strategies to fight flooding whose consequences were felt most severely in 2012 (Chenal, 2009). The current masterplan, Dakar Horizon 2035, revises the 2010 plan and expands its scope by ten years addressing the inadequacies of the former plan and proposing different functional specificities for the network of urban centers (JICA, 2015).

The continuous expansion of the urbanized area of Dakar has occurred over heterogeneous geological conditions. The topography of Cap Vert is the result of volcanic activity that occurred several million years ago. The Yoff Plateau, as well as Dakar-Plateau and Cap Manuel on the southern tip of the Cap, are twenty to sixty meters above sea level. The area from Medina to Hann constitutes a depression that is only two to seven meters above sea level and experiences occasional flooding. A geological section reveals the geological diversity and history of the Cap (Fig. 2). A 25-m thick layer of volcanic deposits (basalt) is contained between more recent yellow sands and another layer of sands with an average thickness of approximately 30 m. Beneath this is an older layer of clay and marl which is close to the surface at the southernmost point of the Cap and gradually descends northwards (Crevola, Cantagrel, & Moreau, 1994; Noël, Roger, et al., 2009; Noël, Serrano, et al., 2009).

The isthmus connecting Cap Vert to the continent is comprised of clay and sand formations situated, such as the Medina, only several meters above sea level in some areas. Littoral sands on the northern coastline mix with ancient dune sands carried by wind over millennia from the continent. Like on the Cap, these formations are deposited over a layer of clay and marl found between 30 and 50 m below the surface descending towards the north. This region is dotted by depressions known locally as the niayes, which are kept humid throughout most of the year by a freshwater aquifer (the quaternary sands or Thiaroye aquifer) (Barusseau, Castaigne, Duvail, Noël, Nehlig, Roger, & Travi, 2009). The permeability of the sands leads to both the rise of the aquifer during heavy periods of recharge (and surface flooding) as well as the gradual infiltration of pollutants from activities on the surface. As the quality of the groundwater decreased from the 1950s onward, pumping of the aquifer for the drinking water system declined, contributing to a gradual rise in the aquifer and more frequent flooding (Gomis, 1996). The Horizon 2025 masterplan, as well as a more extensive drainage management project by the Municipal Development Agency, recommend resuming the pumping of the aquifer for irrigation (ADM, 2012; Cities Alliance Project, 2010). The quaternary sands aquifer extends from the isthmus into the Cap where it is known as the infrabasaltic aquifer.

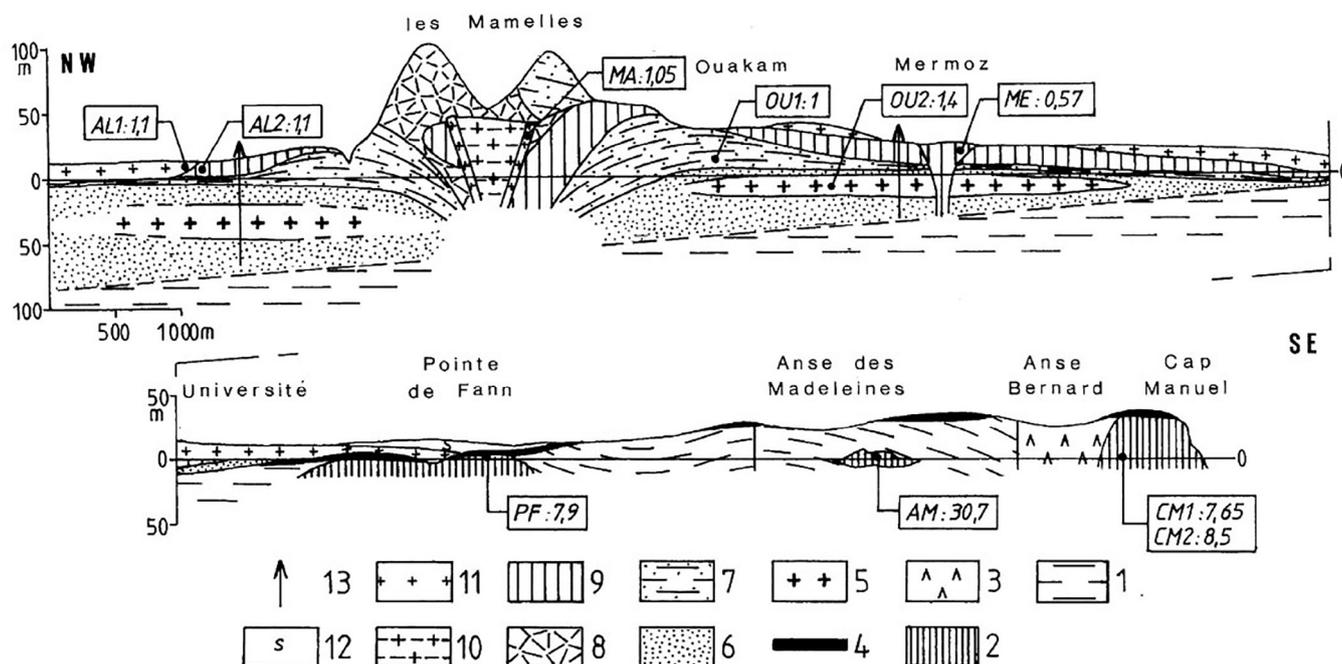


Fig. 2. Geological section from the north of Yoff to Cap Manuel in the south passing through Les Mamelles. 1: Sedimentary tertiary, 2: Tertiary lavas, 3: Tertiary tuffs, 4: Ferruginous cuirass, 5: Medium volcanic ensemble, 6: Infrabasaltic sands, 7: Volcanic surge deposits, 8: Strombolian scorial, 9: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

Its location beneath the impervious volcanic layers protects it from infiltration from surface pollutants and flooding ([Crevola et al., 1994](#)).

Current planning challenges facing Dakar include the scarcity of land, flooding and the availability of energy for the population. The underground resource of main concern is obviously groundwater as both a source of potential conflict (flooding) and of synergy (drinking or irrigation). Given the scarcity of land and the planning imperative to avoid urban sprawl, strategies of densification will raise questions about how and where to build. The Horizon 2035 plan and Municipal Development Agency drainage strategy do not address the potential multifunctionality of the urban volume. What is the role of excavated material? Where could infrastructure or urban spaces be placed underground? If the provision of energy is an issue, what is the potential for geothermal to complementary hydroelectric or photovoltaic systems? The fact that Dakar has not identified a pressing need is not a sufficient reason to neglect, or worse, render alternatives inaccessible for the near or distant future.

### 3 Potential: subsurface and surface

#### 3.1 Subsurface: groundwater, geomaterials, buildable space, and geothermal energy

As mentioned in the introduction, potential is evaluated here without regard for existing needs, projects or desires of the local population. Although important, these dimen-

sions concern the development of potentiality as it is appreciated by actors in an urban area and must be addressed later in the planning process. In the case of Dakar, information on the geological formations and their depths was first approximated using the geological maps of the surface and subsurface downloaded from the Direction des mines et de la géologie ([Noël, Roger, et al., 2009; Noël, Serrano, et al., 2009](#)) and vectorized using supervised classification in ArcGIS, digitized borehole data from the DPGRE (Direction de la gestion et la planification des ressources en eau) ([GKW Consulting, 2004](#)) and topographical data acquired by the author from the ANAT (Agence nationale de l'aménagement du territoire). Expressing the geological formations in terms of geotypes ([Parriaux & Turberg, 2007](#)), there are nine major families of geological formations in Dakar. [Table 1](#) provides an overview of the geotypes including the geological formations they include and a short commentary on their main properties. In the first fifteen meters of ground, the six most frequent are littoral (coastal) sands, plains alluvium, windblown dune sands, alternating limestone and marl, lava and pyroclastic rocks ([Fig. 3](#) and [Table 1](#)).

The relative potential of the geotypes for each resource was quantified using the matrix calculation proposed by the Analytical Hierarchy Process. This process was conducted in two phases for each resource potential: First, quantification of the relative potential of geotypes by pairwise comparisons performed by experts. Second, quantification of the relative importance of the geotypes in relationship to the thickness and depth of the groundwater.

Table 1  
Six most frequent geotypes in the first fifteen meters of Dakar's geology with a brief description of their properties (source of formation codes and descriptions: Barusseau et al., 2009).

Geotype Name	Geological Formations	Description
Plains alluvium	Fz (clay, sand and pebbles) CF (argillaceous sand)	Clayey sands with some gravel, when saturated, highly conductive; more likely to be saturated where there is a lower gravel content
Dune sands	Red sands (Dv-y), white sands (Dlz4) et yellow dune sands (Dlz3)	Sands blown in by the wind. Tend to be very smooth and unstable
Littoral Sands	Shelly (Sgz), beach (Mz2-4) and littoral sands	Sands produced by water erosion of rocks and shells; granularity and shape good for aggregates; conductive where saturated and likely to hold groundwater
Alternating marl and limestones	Alternating marlstone-limestones (e5b, e5c, e4b5, e4b1-4) Shelly limestone and marls (e1)	Marlstone (clay and silt) with limestones; relatively stable when excavated; the clay holds water easily, which may improve its thermal conductivity
Lava	Streams of hawaiiite (d5b, m5b, scn5b) and basanite (4b, 3b)	Ancient lava streams that have cooled; very solid and stable, good for construction and relatively impervious to water
Pyroclastic rocks	Volcanic tuff (5tf, scr5tf, 3tf, 2tf)	Cooled volcanic ash from eruptions; solid, but less impervious to water and having a lower potential thermal conductivity

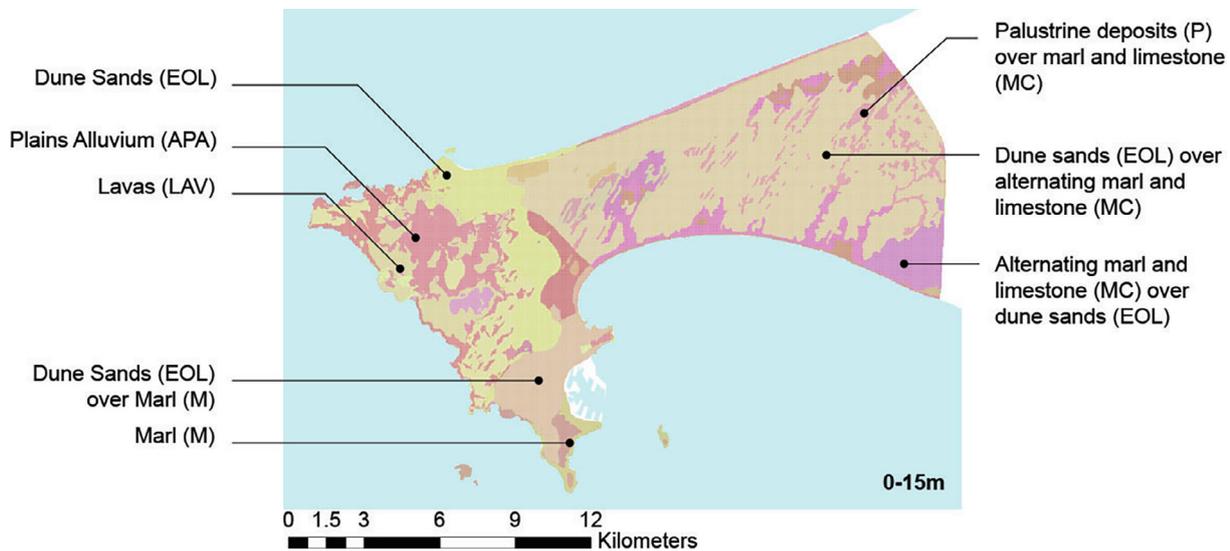


Fig. 3. Distribution of geotypes at 0–15 m (main sources: Noël, Roger, et al. (2009) and Noël, Serrano, et al. (2009)).

For the first phase, nine experts with training in geology, hydrogeology or geomorphology were recruited during a two-week visit to Dakar by the author and a professor of geology from Switzerland. Pairwise comparisons were made between geotypes using a web questionnaire developed in TypeForm<sup>2</sup> and submitted to the experts. To avoid comparisons between geotypes whose potentials experts deemed identical, an initial phase of the questionnaire asked the respondents to evaluate the individual potential of each geotype for its resource potential. This method, adapted from the one proposed by Saaty and Vargas (2012), grouped the geotypes, reducing the number of pairwise comparisons to be made by the experts. The exercise was completed by two of the nine experts from Dakar (a geomorphologist and a hydrogeologist) as well as a professor of geology from Switzerland as a basis of comparison. The responses, where they varied greatly, were

verified by correspondence with the experts. These kinds of exchanges often uncovered local particularities of a geotype and, in particular, revealed a limit in local knowledge about the geothermal potential of certain geotypes. This was because such systems, even for geocooling, are currently rare in Dakar. In this latter case, to avoid inadvertently excluding geothermal potential, expert opinion was replaced with the theoretical thermal conductivity of the geotypes in saturated conditions (where they are more conductive).<sup>3</sup>

The first phase of the evaluation of resource potential resulted in a score per resource for each geotype. The second phase adopted the same pairwise comparison strategy, but this time took the score of the geotype as a criterion and assigned a relative level of importance in relationship to the depth of groundwater and to the thickness of the infrabasaltic aquifer. The comparisons were conducted by

<sup>2</sup> [www.typeform.com](http://www.typeform.com).

<sup>3</sup> For more detailed information on the AHP exercise, please see Doyle (2016a, 2016b).

the author with the idea that the geotype potentials were of overall greater importance than either the depth of groundwater or the thickness of the aquifer. Including aquifer data helped to differentiate areas where the geotype potential may be homogeneous but where the influence of the level of saturation plays an important role. The groundwater criteria were addressed in the aggregation process (basically simple addition) as either positive or negative depending on the resource: The presence of groundwater may contribute positively (better geothermal conductivity) or negatively (water infiltration in excavations or basements) to the evaluation of resource potential.

Buildable space potential (understood as the ability to support a foundation) tends to be higher in the volcanic formations of the Yoff Plateau as well as in the marl and alternating marl and limestone. In the first fifteen meters (not including existing utilities or basements since this information was not available), the potential is highest on the plateau and along the northern coast and across the isthmus where the groundwater level is lower within the sand and clay formations (Fig. 4(a)). The distribution of potential over the isthmus corresponds principally to the areas adjacent to but at a higher altitude than the niayes. Deeper than fifteen meters, the potential drops significantly, reflecting not only the geotypes but also the level of saturation of the ground.

The geotypes that include the geomaterials most favorable for use on or off site are the volcanic formations and, to a lesser extent, the dune sands. In the first fifteen meters, the areas where geomaterial potential is highest include a large area of the Yoff Plateau where most of the dune sands and volcanic formations are found, as well as on the southern tip of the Cap and in areas along the southern coast of the isthmus (Fig. 4(b)). The sand and alluvium geotypes have a permeability that would make the presence of groundwater likely and, when accounting for the actual presence of groundwater, the distribution of groundwater potential in the first fifteen meters covers most of the areas where flooding has occurred south and northeast of the Yoff Plateau, as well as over the isthmus (Fig. 4(c)). Geothermal potential (based on ground saturation and thermal conductivity) is highest in the volcanic and marl formations particularly where the presence of groundwater is high. Geothermal conductivity in the first fifteen meters is highest on the southern part of Cap Vert, on the western third of the Yoff Plateau and the areas where the groundwater is almost at the same level as the surface (Fig. 4(d)).

### 3.2 Surface: urban potential as accessibility to existing built volume

The potential for building underground is not simply a question of the geology but also of the distribution of activities on the surface. As argued above, the existing urban form is not simply a passive indicator of demand for underground space but rather a supply for the possible future

evolution of the city—whether surface or subsurface. This potential concerns the connectivity of one location to other locations at various radii of travel, relying on previous studies whose results suggest that centrality has direct or indirect economic benefits for commercial underground spaces (the activity that tends to be found most in the urban underground). To evaluate centrality in Dakar, a spatial network model was constructed in ArcGIS 10.3 using the street centerline data available freely from OpenStreetMap (OSM) and building envelope data acquired from the ANAT (produced in 2013) and transformed into point data containing built volume information. Centrality metrics (betweenness, straightness, gravity and turn counts; for definitions, see [Sevtsuk, 2010](#)) were calculated using the Urban Network Analysis Toolbox 1.1. plugin ([Sevtsuk & Mekonnen, 2012](#)) at network radii of 100, 200, 400, 800, 1600 and 3200 m. Multiple radii and metrics were adopted in order to give each building a centrality profile rather than presume that movement between buildings in Dakar follows only one type of local logic (least number of turns, shortest distance, etc.) or occurs only at one distance. There is no local rail or subway system in Dakar, and thus the network model only included movement on streets (including those taken by the ‘fast car’ bus system) or pedestrian paths (when available in OSM).

The centrality profile was established using a principal component analysis (PCA) performed on the twenty-four centrality metrics in SPSS, which produced three main components: The first principal component (PC), ‘pervasive global centrality’, captured the distributions of gravity and straightness metrics from 400 to 3200 m. The second, ‘pervasive local centrality’, described the metrics at 100, 200 and 400 m and the third, ‘pervasive path centrality’, addressed the betweenness metrics from radii of 400 to 1600 m. The PCA assigns to each building a quantity indicating its degree of similarity to each component, which can be visualized. Mapping the first PC picks out the areas that are highly central (accessible) at the largest distances (Fig. 5(a)). They appear as clusters following the main arteries northward from the southern tip of the Cap, from the Plateau to Grand Dakar and Parcelles Assainies (a neighborhood from the 1970s), as well as the older sections of Pikine on the isthmus. The spatial distribution of scores for ‘pervasive global centrality’ also identifies the overall separation of the industrial area (along the eastern coast of the Cap) from the rest of the Cap.

Mapping the ‘pervasive local centrality’ PC (Fig. 5(b)) reveals a series of local centers, including Ouakam, Ouest Foire, Dalal Jamm and Mbao, which, interestingly, have all been identified in the Horizon 2035 master plan as targeted development areas. In comparison to pervasive global centrality, the high degree of pervasive local centrality means that these nodes, in their geometry and relationship to built volume, support highly local movement but are less connected at higher radii. This may be for historical reasons: the growth of Ouakam, for instance, was fueled by a military base installed in the early twentieth century.

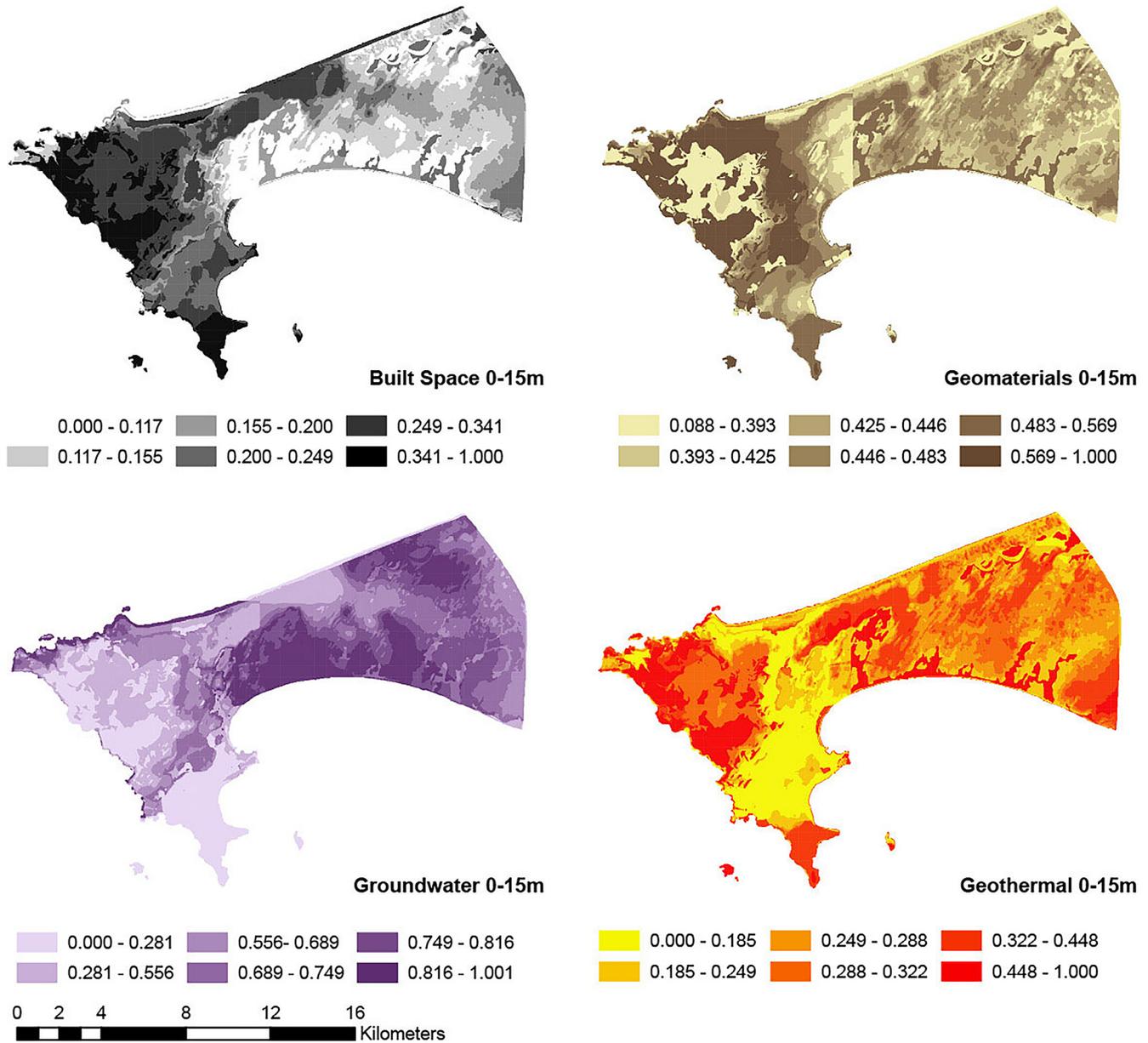


Fig. 4. Underground potential for four resources: (a) buildable space, (b) geomaterials, (c) groundwater, and (d) geothermal, combining geotype evaluations by local experts, groundwater data and aquifer data.

However, the base's closure slowed its growth as a center (the current masterplan seeks to reverse this). The 'pervasive path centrality' nevertheless reveals Ouakam's historical link to the citywide road network. A map of the distribution of similarity scores for this PC shows that, from 100 to 3200 m, there is at least one major axis in Ouakam that would be crossed at shortest distances between origins and destinations weighted according to built volume (Fig. 5(c)). Of course, these metrics do not indicate actual movement but rather suggest a possibility for movement based simply on their geometry and distribution of buildings.

The centrality profiles contribute to an evaluation of underground space potential because centrality for activi-

ties such as commercial can offset the cost of underground construction by being close to potential clientele (passersby or critical masses of people) commanding higher rents or guaranteeing greater foot traffic. The three principal components were converted in ArcGIS from vector to raster data, normalized, and combined with the geotype space potential as well as elevation data used to capture the benefit of being at higher altitudes away from sea level and flood zones. The resulting map shows how centrality contributes to the increase in the potential for underground space in central areas and along important axes (Fig. 6). If Dakar Plateau remains a place of high underground space potential, the Medina just north of Cap Manuel has a degree of centrality that would make it more

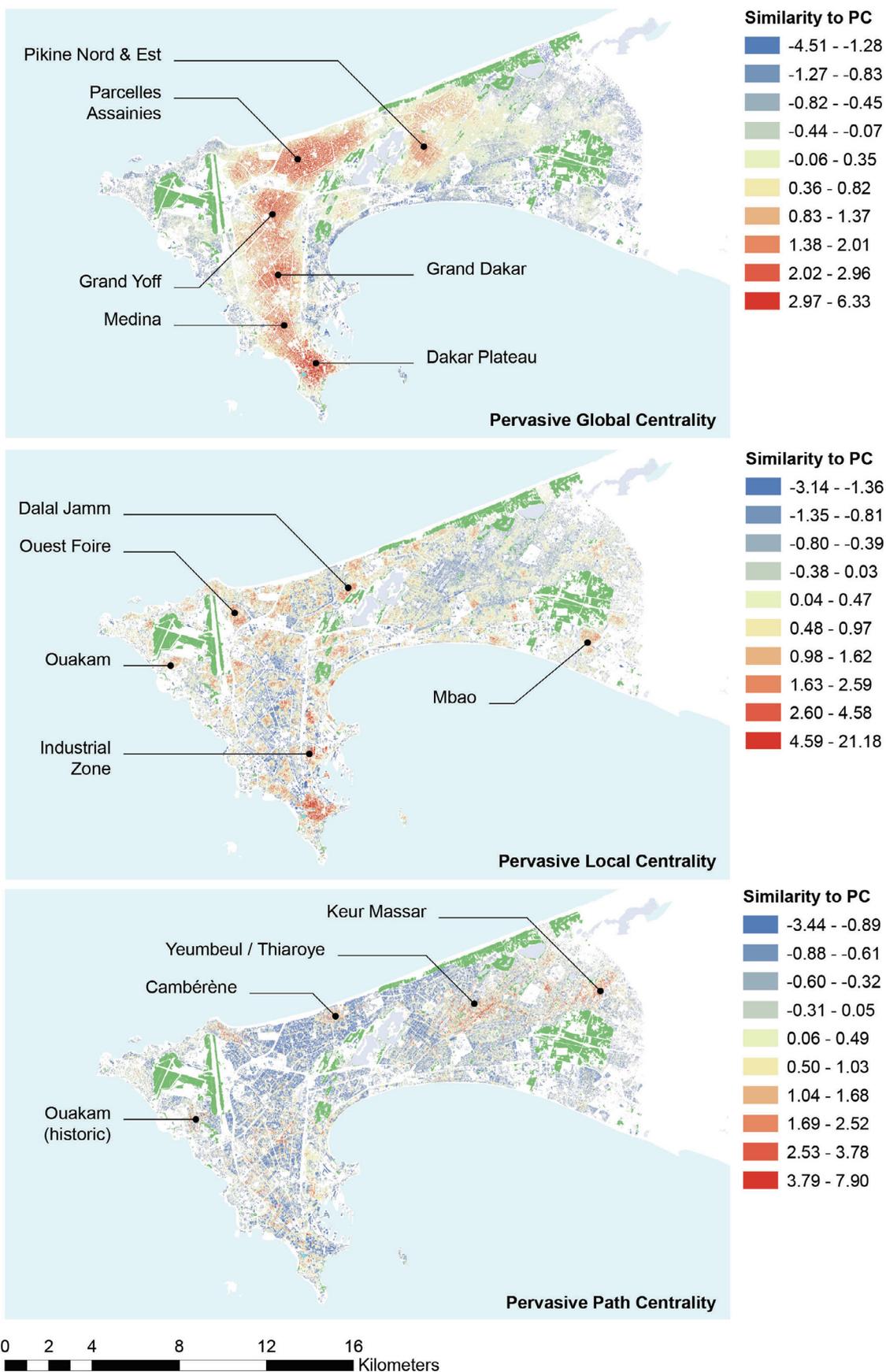


Fig. 5. Three categories of pervasive centrality captured using a principal component analysis run on multiple centrality metrics.

favorable to underground construction despite having less favorable geological conditions (compared with Fig. 4(a)). The same is true for the historic sector of Ouakam and for portions of Yeumbeul and Thiaroye, as well as for Keur Massar and Mbao. Of course, in many of these places, underground construction could be in conflict or generate synergies with the use of other underground resources. It is imperative to consult underground potentials as a group (and of course to cross them with other surface conditions, such as population density).

#### 4 Aggregating underground potential and indexing multilevel combinations

The objective in evaluating underground potential is to arrive at a single map where all four potentials can be consulted at once. One strategy, which has been tested elsewhere (in Geneva, see Blunier, 2009; in San Antonio (Texas), see Doyle, 2016a, and in Hong Kong, see Doyle, 2016b, Chapter 3.2), combines the four resource potential maps using the analytical hierarchy process and assigning relative scores to each resource depending on an overall planning goal or objective. In Dakar, the objective was less to subject the mapping outcome to predefined needs than to explore the overlaps in resource potentials. As the scores for each resource are normalized between zero and one, the

aggregate map for underground potential is simply the addition of the four layers (see Fig. 7).

The combined map of potentials in the first fifteen meters (Fig. 7) reveals the distribution of high and low potential. It highlights the areas on the Cap where the geology is suitable for construction and where use of excavated materials is possible while also being suitable for geothermal systems. The high potential of Yoff Plateau and Dakar-Plateau is clearly the result of the overlap of the space, geomaterial and geothermal potential maps. In the lower-lying areas between the two plateaus, from Medina to Hann, the potential is lower reflecting the lower potential scores of both the geothermal potential and the groundwater potential. On the isthmus, the combination is less straightforward. The zones of lowest potential (blue to yellow) correspond to areas of low space and geomaterial potential but are the areas where combined geothermal and groundwater potentials are the highest (cf. Fig. 4). The geological formations along the southern coast of the isthmus (alternating marl and dune sands) appear to have relatively high scores for all four resources. The dunes in the northern half of the isthmus have relatively high scores that appear to derive, near Cambérène, from high space, geothermal and geomaterial potentials and, near Guédiawaye, from an additional groundwater potential. The coloring of the map is therefore somewhat misleading—the

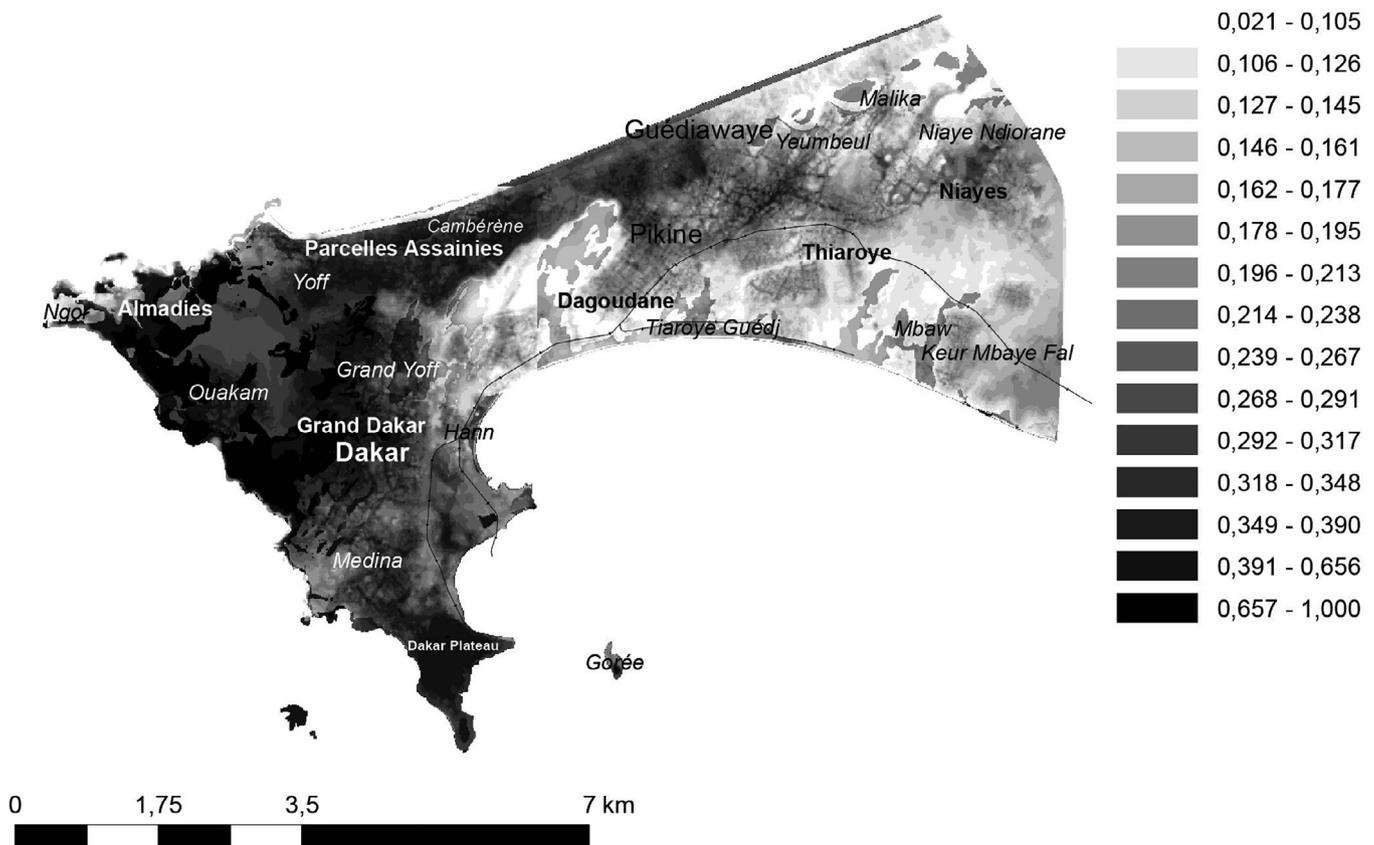


Fig. 6. Combination of the pervasiveness centrality metrics with the first fifteen meters of underground space potential.

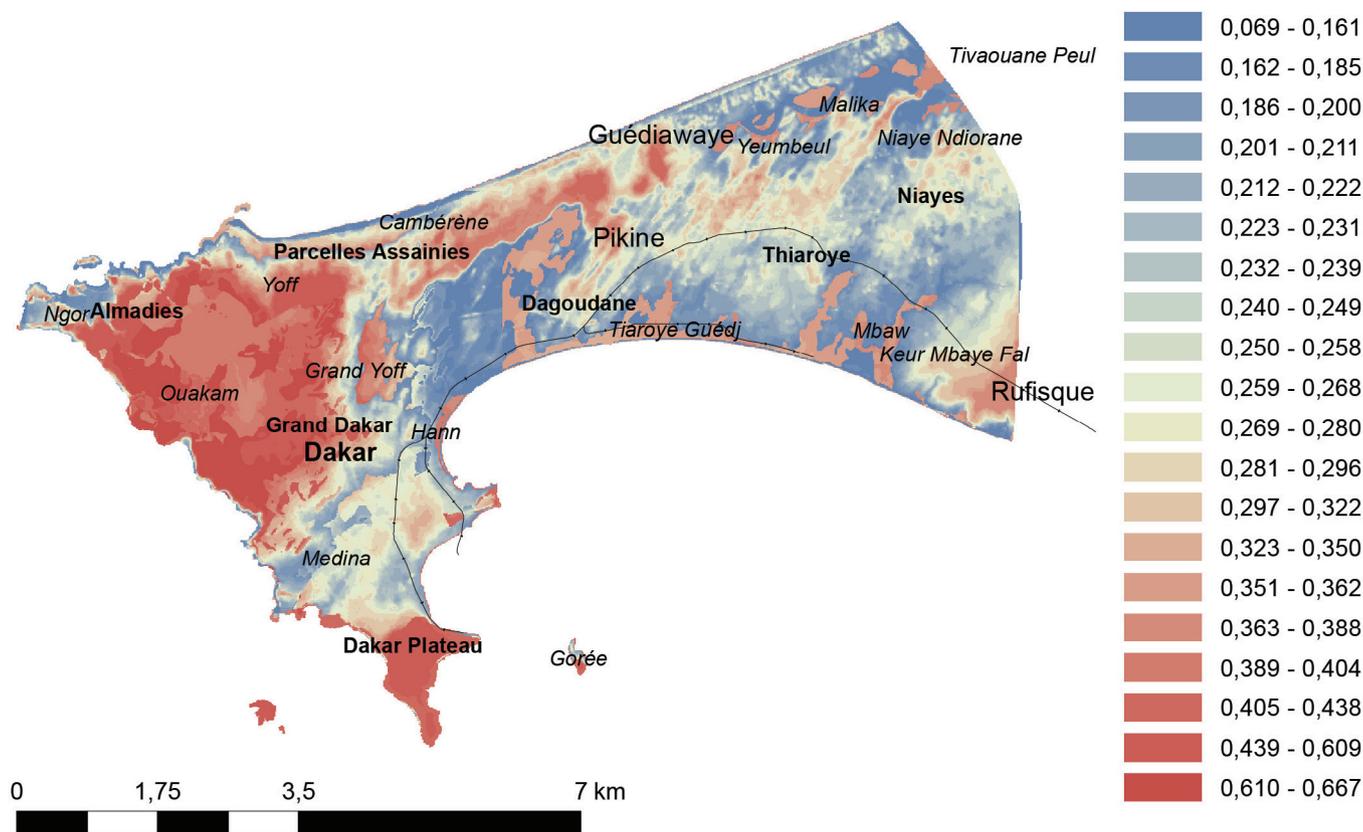


Fig. 7. Combined underground resource potential at 0–15 m from low (blue) to high (red).

same color in one part of the map does not indicate the same combination of potentials as another part. Furthermore, this map is only dealing with the first fifteen meters of geology, which changes with increased depth.

Adding the layers together is adequate where their relative values are oriented towards a particular resource or combination of resources but appears unsuitable for meaningful description of multiple resource potentials at three different depths on a single map. Doyle (2016b) explored the use of a similarity search (available in ArgGIS), which produced maps for eight possible combinations of resource potentials. However, this only increases the number of different maps to be consulted and increases the amount of results to interpret. PCA, which was used to identify patterns in the network centrality of buildings, is not useful for the same type of pattern identification because it assumes a linear relationship between input variables. Because the distribution of resource potential cannot be assumed to be linearly correlated, PCA would identify multiple principal components with less of the data distribution described by the initial components.

To handle nonlinear input data and to preserve as much heterogeneity in the original data as possible, the potential scores for the four resources at depths of 15, 30 and 45 m (total of twelve different variables) were used as input vectors in a self-organizing map (SOM). The SOM algorithm projects a nonlinear high-dimensional data space on a low-dimensional space. In other words, it ‘learns’ the underlying

patterns in the data and (unlike clustering) produces an ordered set of indices that capture interrelationships in the data (Kohonen, 2001). A SOM does not produce a geographical map but rather a topological mapping. In the case of Dakar, this can be understood as a single node (low-dimensional point) that represents all the locations in the city that have similar distributions of potential scores at all three depths. These nodes or indices can be visualized in geographical space when the low-dimensional space is one-dimensional rather than two-dimensional—this is an uncommon, but promising, application of SOM in geographical sciences and represents an extension beyond its use as a mere visualization tool (Moosavi, 2015, 2017).

A one-dimensional SOM run on the four resource potentials at three depths described the topology with sixteen nodes—the number that had the lowest quantization score (average distance from the nodes to the vectors they index). Mapping the distribution of the nearest nodes to each grid cell illustrates the zones characterized by similar resource combinations (Fig. 8). The SOM revealed a particular weakness in the underlying data: The limit of the model of the infrabasaltic sands aquifer, which should emerge more gradually from its confined state beneath the basalt formations to its unconfined state where it joins the quaternary sands aquifer deeper than fifteen meters. While keeping this weakness in mind, the order of the nodes (from blue to yellow to red) indicates zones whose characteristics are similar. Starting with the first node

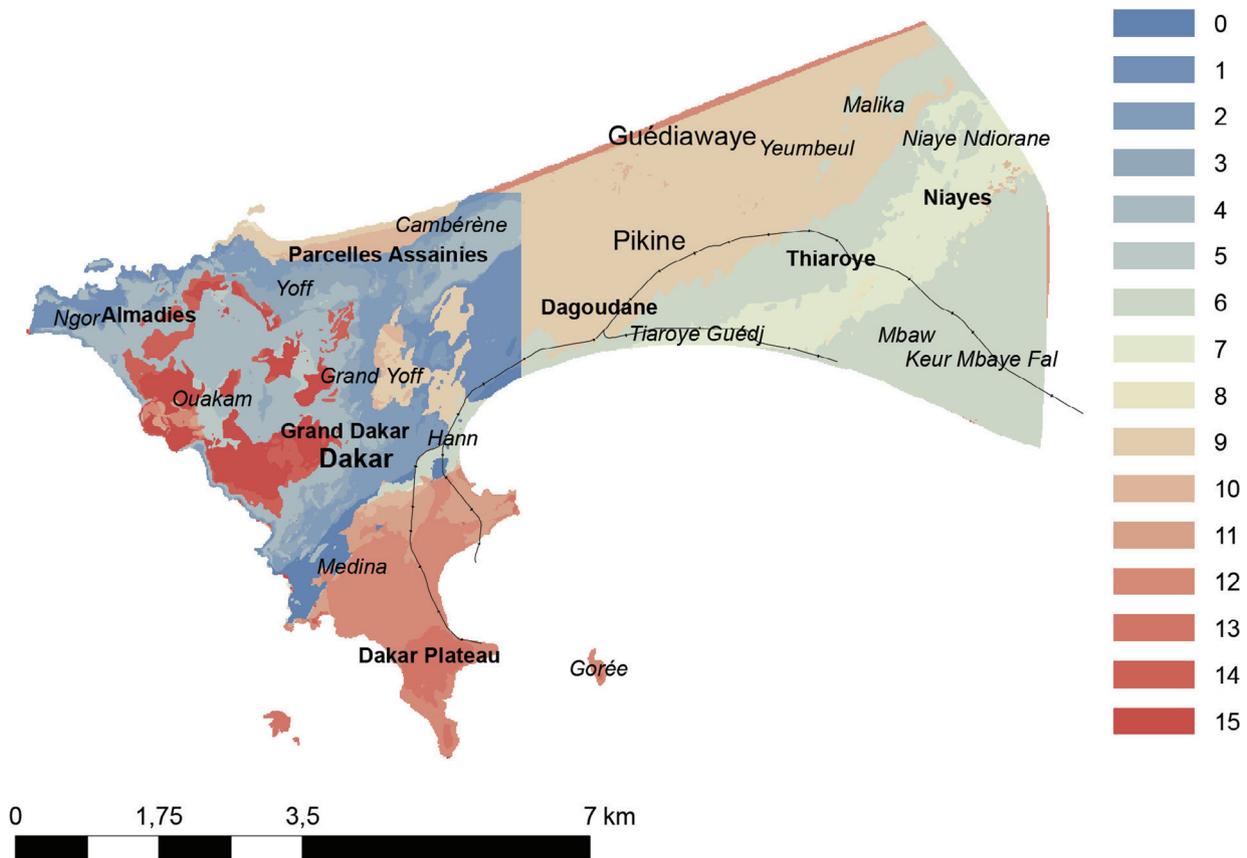


Fig. 8. Distribution of the indexes of the one-dimensional SOM algorithm, which identified sixteen distinct patterns of combined resource potentials and represents more explicitly the differences between resource combinations.

(blue), there are a series of zones from the southern part of the Yoff Plateau surrounding it as the blue moves towards green and gradually rising to most of the plateau surrounding the volcanic (red) areas, which the SOM identified as distinct in their context. Around the sixth node, the particularities of the isthmus along the southern shore and onto large areas around Keur Mbaye Fal and Mbaw are picked out with a gradual northward progression of similarity along the isthmus and eventually including areas along the north coast of the Cap and inland east of Grand Yoff. The eleventh node picks up a zone surrounding the dark orange areas on the slopes of the Yoff plateau, and the remaining nodes index the areas on the southern tips of the Cap including Cap Manuel, the islands and eventually the dark red areas scattered over the Yoff Plateau.

The simple addition of the resource potentials identified three areas with higher than average underground potential: Dakar-Plateau, the Yoff Plateau, in particular Ouakam, and Pikine (Fig. 7). The SOM, however, reveals major differences in their resource potentials. The area of the Cap, including Dakar-Plateau, is characterized geologically by dune sands over marl. It has a middle to higher-than-average buildable space potential increasing downward to 45 m, mid-range geomaterial potential at all depths, low groundwater potential and low to medium geothermal potential. This suggests that Dakar-Plateau,

and places such as it (indexed by the same node), may be good candidates for shallow to deep underground construction and may have decent potential for geomaterial use on site or elsewhere with only low potential for geothermal or groundwater production (although the marl is highly absorbent). Ouakam is situated in the dark red areas (Fig. 8) of lava and plains alluvium. It is characterized by a high potential for construction, for geomaterial use and geothermal energy but only in approximately the first 30 m. The infrabasaltic aquifer is confined beneath these formations and has a low potential for all resources except groundwater. The area around Pikine is situated on the isthmus over alternating marl and limestone formations covered by dune sands. Although its geometry and building density characterize it as centrally located at the regional and local scales, the tendency for the marl to expand and contract during the rise and fall of the aquifer means that, in general, the part of the isthmus sharing the same index as Pikine has low potential for underground construction. The possibility of using extracted geomaterials is medium to low and depends on the quality and ease of separation of the dune sands. The potential for geothermal is about the same in the first fifteen meters but increases as the level of saturation increases. The highest potential, which is unsurprising given the presence of the aquifer and the proximity to sea level, is for groundwater.

This study has not, unfortunately, had the opportunity to share the resulting maps with the local experts consulted. Possibilities for application can only be formulated hypothetically or in terms of a series of questions. The indexing of the four resource potentials at various depths using the SOM algorithm (versus a simple aggregation by addition) has the advantage of producing a single geographical map for consultation by decision makers, planners or experts. It has the disadvantage of not providing a stable characterization—that is, if data is updated or added, the number of optimal nodes may change. Of course, the actual significance of this change may be quite small and would have to be tested. If, for instance, geographical data on the movement of the aquifer was added, the model would have to learn these changes over time and perhaps in real time. With such time-series data, the characterizations (assigned nodes) would stabilize around repetitive patterns in time but might shift suddenly in the case of a sudden change in the underlying data. Such an application may be beneficial for identifying measures to apply locally or regionally by decision makers from the different municipalities when one area suddenly changes categories (as in a flood or a sudden, unusual rise in groundwater levels). These are possible investigations for future research.

## 5 Conclusions: resources to needs, from data-poor to data-rich settings

The Dakar case study was an opportunity to examine urban underground potential on a continent that has received little attention from research on the underground in an urban context and to test the Deep City methodology in a context where digital geographical data was limited. This limitation, although pointing out the necessity for improvement, is understandable in a city where the production of data has been limited to the groundwater resource. It is less a disadvantage than an advantage: Dakar still has the opportunity to coordinate the planning of its underground resources in a rational and sustainable fashion. As the maps produced by this study show, the city is characterized by zones of different combinations of resource potentials from the surface to 45 m deep. Of course, the evaluation presented here should be followed up with more detailed local investigations and only provides a general overview for the planning process.

This study is not only about the city of Dakar but also about the continued improvement of a mapping method developed by the Deep City project. One of the major challenges facing a cartographical method such as this one is the ability to present data of different geographical and measurement scales on a single map. The approach using geotypes, combined with the Analytic Hierarchy Process (AHP), proves effective for translating the relationships between individual criteria into quantitative measures. This approach falls short, however, in the combination of potentials where no single objective can orient the relationship between criteria. As demonstrated here, this is the

possible benefit of the self-organizing map (SOM). The SOM does not establish metrical, but topological relationships between the criteria—the underlying patterns in their structure that are independent of measure. Further testing is needed, of course, to explore the limits of this approach.

Every city should include its underground in the planning process even if the result is protection rather than exploitation or prevention rather than intervention. The mapping method proposed here can provide cities with a quick overview of their resource potentials without needing a large amount of data. In principle, more data is better. However, this poses challenges in practice. As the number of criteria increases, so does the difficulty of establishing the relationships between these criteria. Where only one resource potential (or a predetermined combination of potentials) is of interest, multicriteria decision-making methods such as the AHP can respond without problem. They fall short, however, when there is no desired outcome, when the multiuse potential of the resources is still at its maximum. The study presented here is only a first step in confronting some of the difficulties faced by these methods and to explore the SOM as a possible alternative. Although the area of application here was the urban underground, the questions it raises are of concern for the ability of urban planning in general to respond to increasing amounts of multidimensional spatial information.

## Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Declaration of Competing Interest

The author wishes to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

## References

- ADM (2012). *Plan directeur de drainage pluvial* (Final Report No. 3). Dakar: Agence de développement municipal (p. p. 320).
- Barusseau, J.-P., Castaigne, P., Duvail, C., Noël, B. J., Nehlig, P., Roger, J., ... Travi, Y. (2009). *Notice explicative de la cartographie multicouches 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, p. 245.
- Bélanger, P. (2007). Underground landscape: The urbanism and infrastructure of Toronto's downtown pedestrian network. *Tunnelling and Underground Space Technology*, 22(3), 272–292.
- Blunier, P. (2009). *Méthodologie de gestion durable des ressources du sous-sol urbain* (Doctoral Dissertation). Lausanne.: EPFL. <http://library.epfl.ch/theses/?nr=4404>.
- Boisvert, M. A. (2011). *Montréal et Toronto: Villes intérieures*. Montréal: Presses de l'Université de Montréal.
- Chenal, J. (2009). *Urbanisation, planification urbaine et modèles de ville en Afrique de l'Ouest: Jeux et enjeux de l'espace public* (PhD in Architecture, City, History). Lausanne, Switzerland: École polytechnique fédérale de Lausanne.

- Cities Alliance Project (2010). Stratégie de développement urbain du Grand Dakar (Horizon 2025) (Urban Masterplan No. P099673) (p. 74).
- Crevola, G., Cantagrel, J.-M., & Moreau, C. (1994). Le volcanisme cénozoïque de la presqu'île du Cap-Vert (Sénégal): Cadre chronologique et géodynamique. *Bulletin de la Société Géologique de France*, 165(5), 437–446 (in French).
- Doyle, M. R. (2016b). *Potentialities of the urban volume: Mapping underground resource potential and deciphering spatial economies and configurations of multi-level urban spaces* (PhD in Architecture and the Sciences of the City). Lausanne, Switzerland: Swiss Federal Institute of Technology Lausanne (EPFL). <https://doi.org/10.5075/epfl-thesis-7328>.
- Doyle, M. R. (2016a). From hydro/geology to the streetscape: Evaluating urban underground resource potential. *Tunnelling and Underground Space Technology*, 55, 83–95.
- Doyle, M. R. (2017). 'Resources to Needs': A paradigm for addressing the potentiality of the urban volume. *Urban Planning*, 2(1), 6.
- El-Geneidy, A., Kastelberger, L., & Abdelhamid, H. T. (2011). Montréal's roots: Exploring the growth of Montréal's Indoor City. *Journal of Transport and Land Use*, 4(2), 33–46.
- Gomis, R. (1996). *L'aquifère des sables quaternaires au nord de la presqu'île du Cap-Vert (Sénégal): Morphologie déduite des données hydrogéologiques et géophysiques (sondages électriques). Analyse de la vulnérabilité de la nappe à l'invasion saline dans la zone de Pikine* (Master's Thesis). Dakar: Cheikh Anta Diop University.
- Consulting, G. K. W. (2004). *Projet Eau à Long Terme — Études hydrogéologiques complémentaires* (Intervention report). Dakar: Ministère de l'Agriculture, de l'Élevage et de l'Hydraulique.
- Hillier, B. (2012). The genetic code for cities: Is it simpler than we think?. In J. Portugali, H. Meyer, E. Stolk, & E. Tan (Eds.), *Complexity theories of cities have come of age* (pp. 129–152). Berlin, Heidelberg: Springer Berlin Heidelberg. [http://link.springer.com/10.1007/978-3-642-24544-2\\_8](http://link.springer.com/10.1007/978-3-642-24544-2_8).
- International Tunnelling and Underground Space Association (2012). Report on underground solutions for urban problems (No. 011).
- JICA (2015). *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, République du Sénégal.
- Kohonen, T. (2001). *Self-organizing maps* (3rd ed.). New York: Springer.
- Kohonen, T. (2015). What makes the self-organizing maps (SOM) so particular among learning algorithms?. In V. Bühlmann, L. Hovestadt, & V. Moosavi (Eds.), *Coding as literacy: Metalithikum IV* (pp. 22–25). Basel, Switzerland: Birkhäuser, Part of Walter de Gruyter GmbH, Berlin.
- Li, H., Parriaux, A., Thalmann, P., & Li, X. (2013). An integrated planning concept for the emerging underground urbanism: Deep City Method Part 1 concept, process and application. *Tunnelling and Underground Space Technology*, 38, 559–568.
- Maire, P. (2011). *Étude multidisciplinaire d'un développement durable du sous-sol urbain. Aspects socio-économiques, juridiques et de politique urbaine* (Doctoral Dissertation). Lausanne: Swiss Federal Institute of Technology Lausanne (EPFL).
- Moosavi, V. (2015). Pre-specific modeling: Computational machines in a coexistence with concrete universals and data streams. In V. Bühlmann, L. Hovestadt, & V. Moosavi (Eds.), *Metalithikum IV, coding as literacy* (pp. 132–166). Vienna: Birkhäuser.
- Moosavi, V. (2017). Contextual mapping: Visualization of high-dimensional spatial patterns in a single geo-map. *Computers, Environment and Urban Systems*, 61, 1–12.
- Noël, B. J., Roger, J., Nehlig, P., Serrano, O., Dabo, B., Seck, D., & Duvail, C. (2009). *Carte géologique de la zone d'activité du Cap-Vert à 1/50000. Formations du substratum*. Map, Dakar: GEOTER SAS.
- Noël, B. J., Serrano, O., Duvail, C., Barousseau, J.-P., Diagne, É., & Seck, D. (2009). *Carte géologique de la zone d'activité du Cap-Vert à 1/50000. Formations superficielles*. Map, Dakar: GEOTER SAS.
- Ortiz-Zamora, D., & Ortega-Guerrero, A. (2010). Evolution of long-term land subsidence near Mexico City: Review, field investigations, and predictive simulations: Long-term Land Subsidence. *Water Resources Research*, 46(1).
- Parriaux, A., Blunier, P., Maire, P., Dekkil, G., & Tacher, L. (2010). *Projet Deep city: Ressources du sous-sol et développement durable des espaces urbains*. Lausanne: vdf Hochschulverlag AG an der ETH Zürich.
- Parriaux, A., Tacher, L., & Joliquin, P. (2004). The hidden side of cities—Towards three-dimensional land planning. *Energy and Buildings*, 36(4), 335–341.
- Parriaux, A., & Turberg, P. (2007). Les géotypes, pour une représentation géologique du territoire. *Tracés*, 133(15–16), 11–17.
- Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation*. New York, London: McGraw-Hill International Book Co..
- Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1), 9–26.
- Saaty, T. L., & Vargas, L. G. (2012). *Models, methods, concepts & applications of the analytic hierarchy process* (2nd ed.). New York: Springer.
- Seck, A. (1970). Dakar, métropole ouest-africaine. *Mémoires de l'Institut Fondamental d'Afrique Noire*, 85, 1–516.
- Sevtsuk, A. (2010). *Path and place: A study of urban geometry and retail activity in Cambridge and Somerville, MA* (Doctoral Dissertation). Cambridge, MA: Massachusetts Institute of Technology, Dept of Urban Studies and Planning.
- Sevtsuk, A., & Mekonnen, M. (2012). Urban network analysis. A new toolbox for ArcGIS. *Revue Internationale de Géomatique*, 22(2), 287–305.
- Sinou, A. (1990). *Dakar. Bulletin d'information Architecturales*. Paris: Institut Français d'Architecture.
- Vähäaho, I. (2016). An introduction to the development for urban underground space in Helsinki. *Tunnelling and Underground Space Technology*, 55, 324–328.
- Wallace, M. I., & Ng, K. C. (2016). Development and application of underground space use in Hong Kong. *Tunnelling and Underground Space Technology*, 55, 257–279.
- Zhao, J.-W., Peng, F.-L., Wang, T.-Q., Zhang, X.-Y., & Jiang, B.-N. (2016). Advances in master planning of urban underground space (UUS) in China. *Tunnelling and Underground Space Technology*, 55, 290–307.