Urban Underground Potential in Dakar, Senegal
Reversing the Paradigm of 'Needs to Resources'

Michael R. DOYLE, PhD
Deep City Project
Laboratory for Environmental and Urban Economics (LEURE)
École polytechnique fédérale de Lausanne (EPFL), Switzerland

Abstract

This article presents a mapping method that seeks to provide urban planning with a general 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 is already on the boards. 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 promotes an alternative paradigm of 'resources to needs', 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 as well as for providing a more meaningful mappings of geological and urban data in three dimensions.

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 to be oriented towards single-function infrastructure. This lack of a holistic approach in the planning phase and of a monofunctionality in application has proven problematic. Groundwater extraction in the region of Mexico and Paris has led to subsidence in both cities (Blunier, 2009; Ortiz-Zamora and Ortega-Guerrero, 2010). The moratorium placed by the French capital on pumping for industrial reasons caused the groundwater table to rise and to flood 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 like Toronto and Montreal are cited as exemplary for the successful integration of underground spaces in their urban fabric (Bélanger, 2007; Boisvert, 2011; El-Geneidy et al., 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.

Cities tend to investigate their underground conditions on a needs-only basis and to rarely consult geological maps or sections during the early stages of the planning process. 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 toward sustainability, the underground can assist in increasing urban density without building upwards, but also in protecting open and green spaces on the surface by building underneath (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 et al., 2010, 2004). In contrast to recent underground potential maps or methods produced by cities like Helsinki (Vähäaho, 2016), Hong Kong (Wallace and Ng, 2016) and in mainland China (Zhao et al., 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 towards a particular planning objective, the Deep City project hopes to promote a reversal of the 'needs to resources' paradigm to one of 'resources to needs' in which necessity plays no role in the diagnostic process. This alternative paradigm questions the adequacy of considering all innovative uses of the resource potentials to have been 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 like Geneva (Blunier, 2009), Suzhou, China (Li et al., 2013), San Antonio, Texas (Doyle, 2016a, chap. 3.1), Hong Kong, China and most recently in Dakar, Senegal (Doyle, 2016b, chap. 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 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.

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 model; 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 model is compiled in a geographical information system software like ArcGIS using a common spatial unit that captures the smallest resolution of the data (e.g. 25x25m or 50x50m). The common grid has the advantage of being able to account for different types of data collected at different scales. In order to simplify the geological descriptions for ease of use by non-geologists 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, chap. 3.0) and demonstrated later in this article, the relative resource potentials of each geotype are quantified using the Analytic Hierarchy Process (Saaty, 1990), a multi-criteria 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 to 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 latter 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, for example 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 nearby captive clientele (Maire, 2011, chap. 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, chap. 2). In order 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 and Mekonnen, 2012). Where 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, when 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, 2015, 2001; 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 (Figure 1). European settlement 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, a volcanic landmass connected to the mainland by low-lying sand formations. From the nineteenth century and into the early twentieth, Dakar grew in political and economic importance with the connection of its port to the inner continent by rail (Sinou, 1990). The first masterplan 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).

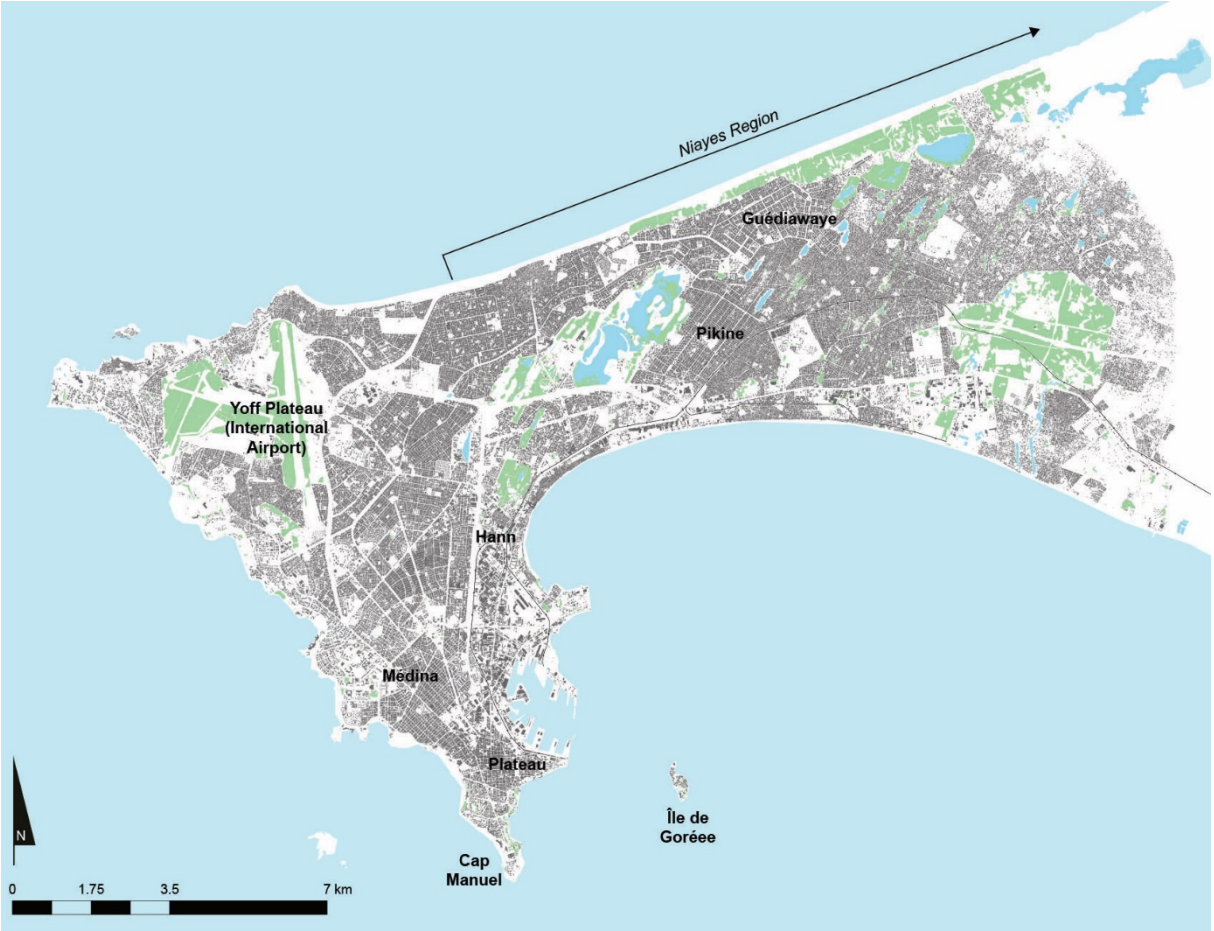

Figure 1. The Cap-Vert peninsula with the Cap (from Cap Manuel to the Yoff Plateau) and the isthmus connecting the Cap to the continent (data sources: Open Street Map; ANAT, Dakar).

With the influx of population following the development of Dakar after the war, the initial masterplan was updated in 1961 (several years after Senegal's independence from France) 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, but the plan dealt more with the management of existing development than propose 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 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, the consequences of which 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 occurring several million years ago. The Yoff Plateau as well as Dakar-Plateau and Cap Manuel on the southern tip of the Cap are both 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 (Figure 2). A 25-meter thick layer of volcanic deposits (basalt) is sandwiched between more recent yellow sands and another layer of sands with an average thickness of about 30 meters. Beneath this is an older layer of clay and marl which is near to the surface

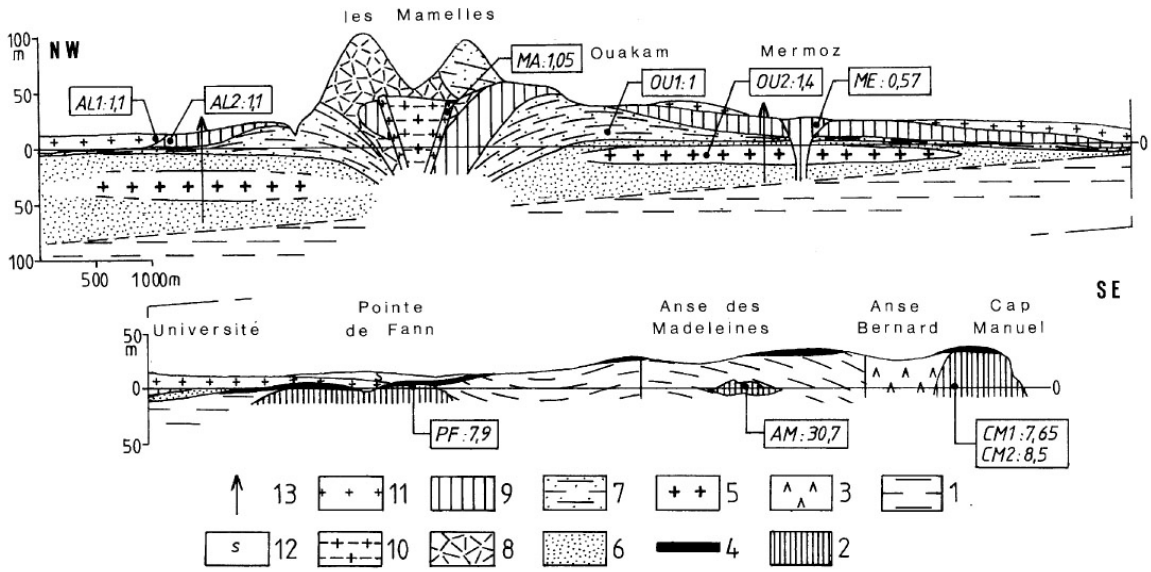

FIG. 4. – Coupe schématique de la côte ouest de la tête de la presqu'île du Cap-Vert montrant les relations entre les formations datées. 1 : Tertiaire sédimentaire ; 2 : laves tertiaires ; 3 : tufs tertiaires 4 : cuirasse ferrugineuse ; 5 : ensemble volcanique moyen ; 6 : sables infra-basaltiques ; 7 : dépôts de déferlantes basales ; 8 : scories stromboliennes ; 9 : coulées d'hawaiites ; 10 : coulées d'hawaiites doléritiques dans le lac de lave ; 11 : coulées d'hawaiites doléritiques ; 12 sables récents ; 13 : sondages.

Figure 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 hawaiite; 10 – Streams of doleritic hawaiite in lava lakes; 11 – Streams of doleritic hawaiite; 12 – Recent sands; 13–Boreholes (source: Crevola et al., 1994, p. 442).

at the southernmost point of the Cap and gradually descends northwards (Crevola et al., 1994; Noël et al., 2009a, 2009b).

The isthmus connecting Cap Vert to the continent is comprised of clay and sand formations situated, like 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 meters 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 et al., 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 of 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. Contained beneath the volcanic layers, which protect 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 complement hydroelectric or photovoltaic systems? The

fact that Dakar has not identified a pressing need is not a sufficient reason to neglect or, worse, render inaccessible alternatives for the near or distant future.

3. Potential: Subsurface and Surface

3.1 Subsurface: Groundwater, Geomaterials, Buildable Space, 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 dimensions concern the development of the 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 et al., 2009a, 2009b) 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 and 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 (Figure 3 and Table 1).

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.
LAVAS	Streams of hawaiite (d5ß, m5ß, scn5ß) and basanite (4ß, 3ß)	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.

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).

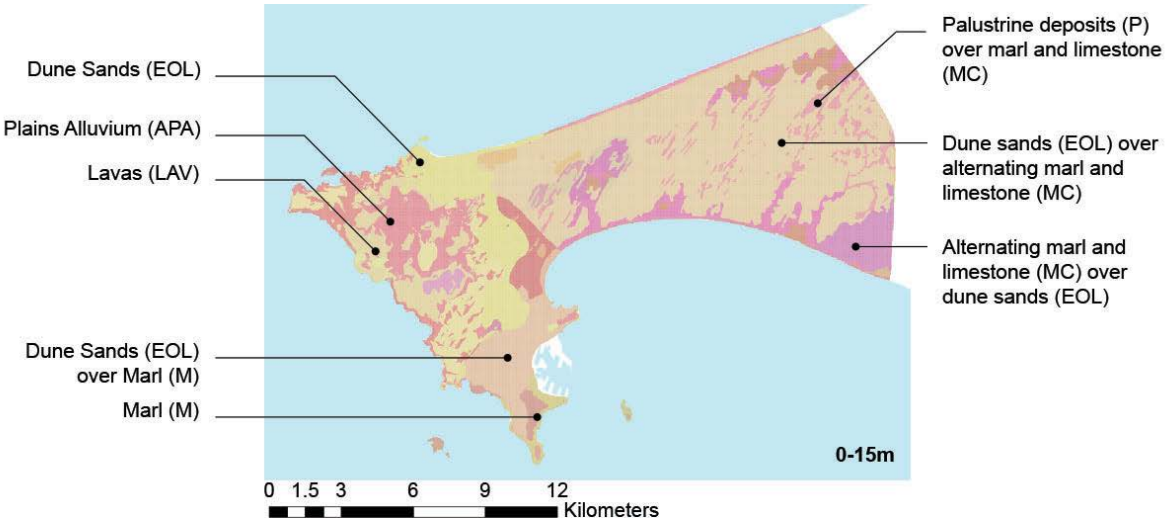

Figure 3. Distribution of geotypes at 0-15 meters (main sources: Noël et al., 2009a, 2009b).

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. 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 and submitted to the experts. In order 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 the 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 lack of general local knowledge about the geothermal potential of certain geotypes (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).

The first phase of the evaluation of resource potential by geotype 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 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, as 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 (Figure 4a). 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 group 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 (Figure 4b). 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 (Figure 4c). 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

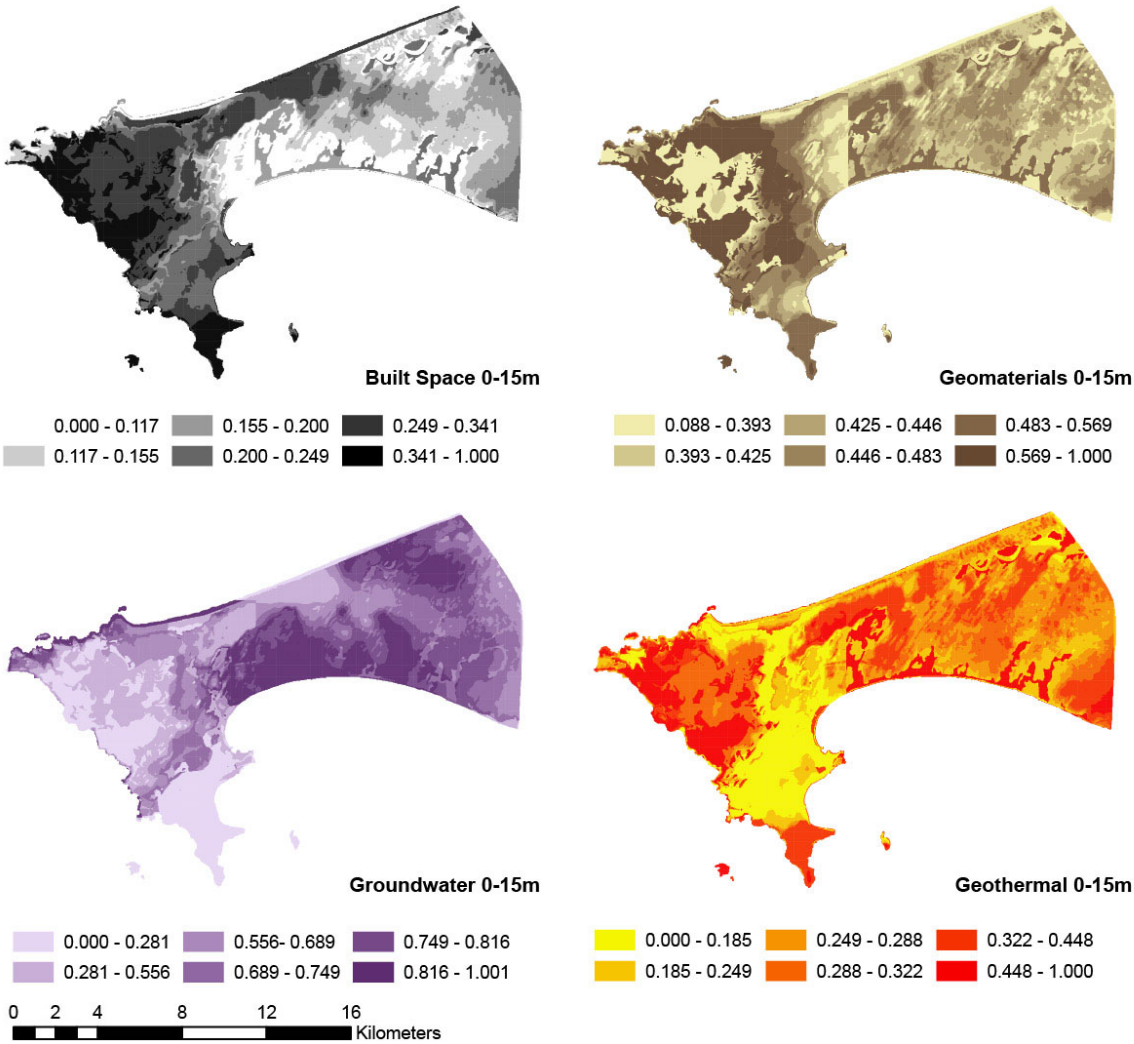

Figure 4. Underground potential for four resources: Buildable space (top left, a); Geomaterials (top right, b); Groundwater (bottom left, c); and Geothermal (bottom right, d), combining geotype evaluations by local experts, groundwater data and aquifer data.

the Yoff Plateau and the areas where the groundwater is almost at the same level as the surface (Figure 4d).

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 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 and Mekonnen, 2012) at network radii of 100, 200, 400, 800, 1600 and 3200 meters. 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, so the network model only included movement on streets 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 meters; the second, ‘pervasive local centrality’, described the metrics at 100, 200 and 400 meters; and the third, ‘pervasive path centrality’, addressed the betweenness metrics from radii of 400 to 1600 meters. 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 (Figure 5, top). 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 (Figure 5, middle) 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, but that later closed, slowing its continued growth as a center (which the current masterplan would like to rectify). The ‘pervasive path centrality’ nevertheless reveals Ouakam’s historical link to the city-wide road network. A map of the distribution of similarity scores for this PC shows that, from 100 to 3200 meters, 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 (Figure 5, bottom). 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 activities like commercial can offset the cost of underground construction by being close to potential clientele (passersby or critical masses of people), commanding higher rents

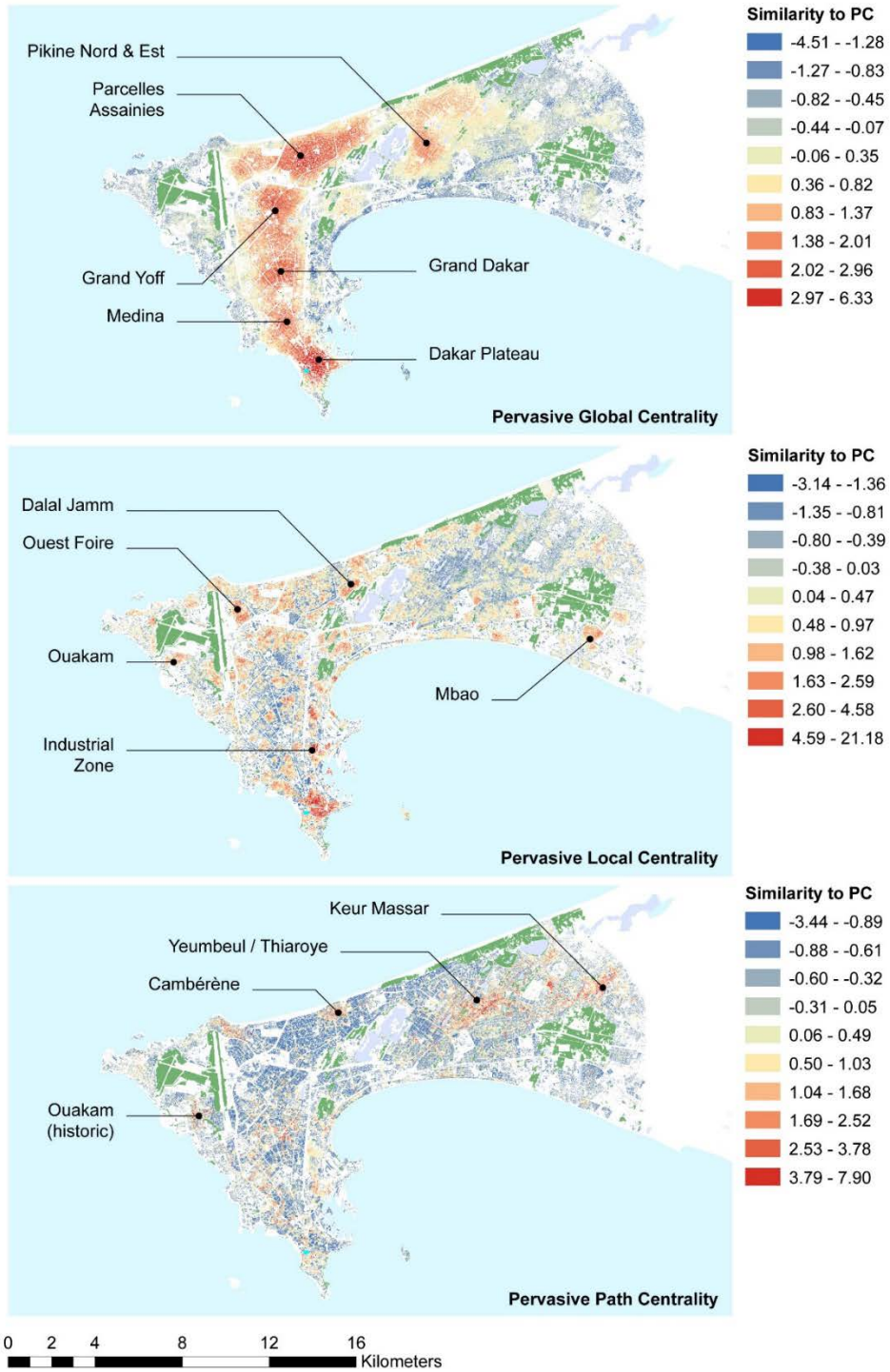

Figure 5. Three categories of pervasive centrality captured using a principal component analysis run on multiple centrality metrics.

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 increase the potential for underground space in central areas and along important axes (Figure 5). 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 favorable to underground construction, despite its being in less favorable geological conditions (comparing with Figure 4a). The same is true

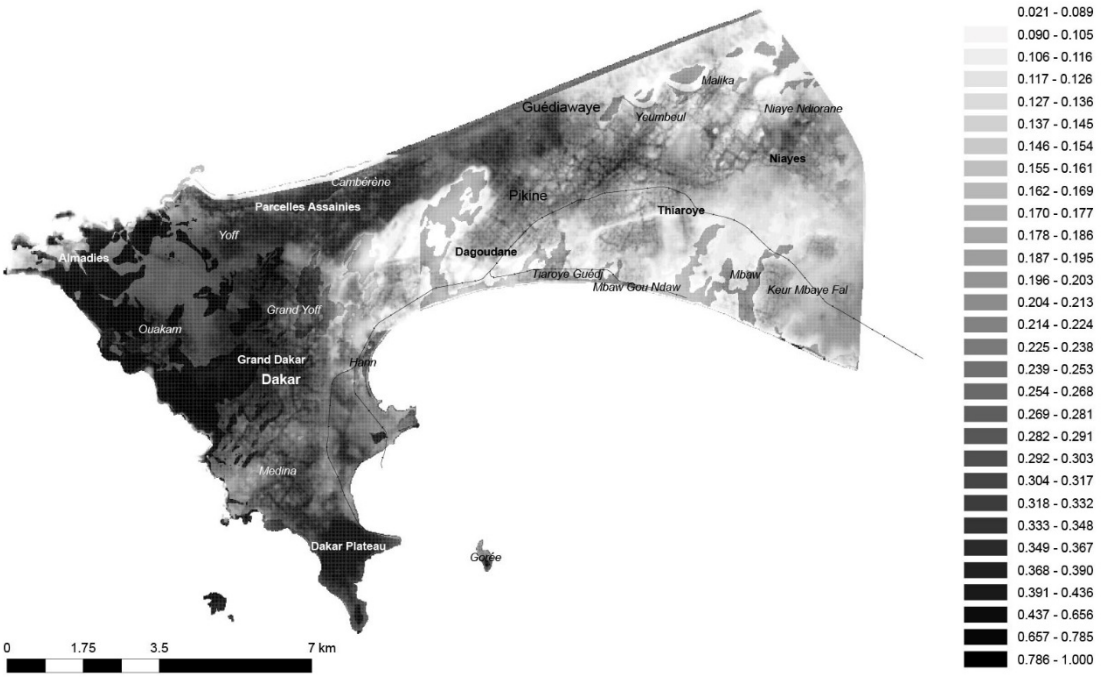

Figure 6. Combination of the pervasive centrality metrics with the first fifteen meters of underground space potential.

for the historic sector of Ouakam and for portions of Yeumbeul and Thiaroye as well as 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 together.

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, chap. 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 together.

The combined map of potentials in the first fifteen meters (Figure 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, 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. Figure 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 same color in one

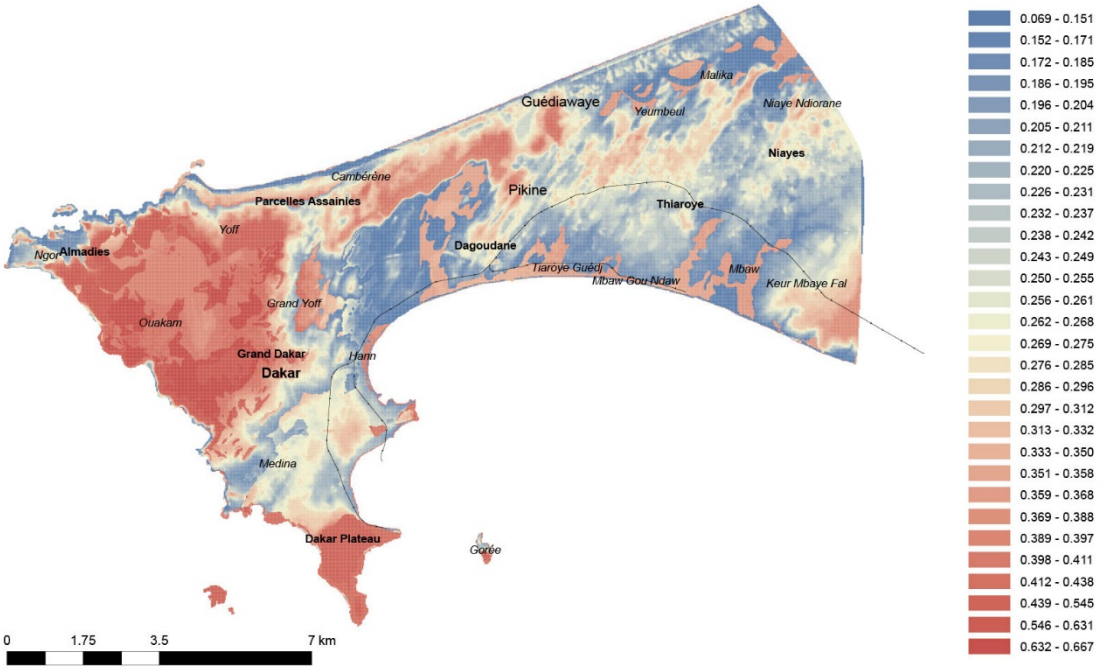

Figure 7. Combined underground resource potential at 0-15 meters from low (blue) to high (red).

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 fragments the information produced. 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, the PCA would identify multiple principal components with less of the data distribution described by the initial components.

In order to handle non-linear 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 meters (total of twelve different variables) were used as input vectors in a self-organizing map (SOM). The SOM algorithm projects a non-linear 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 here 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 extension beyond its use as a mere visualization tool (Moosavi, 2017, 2015).

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 (Figure 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 (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 including eventually 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 Yoff Plateau.

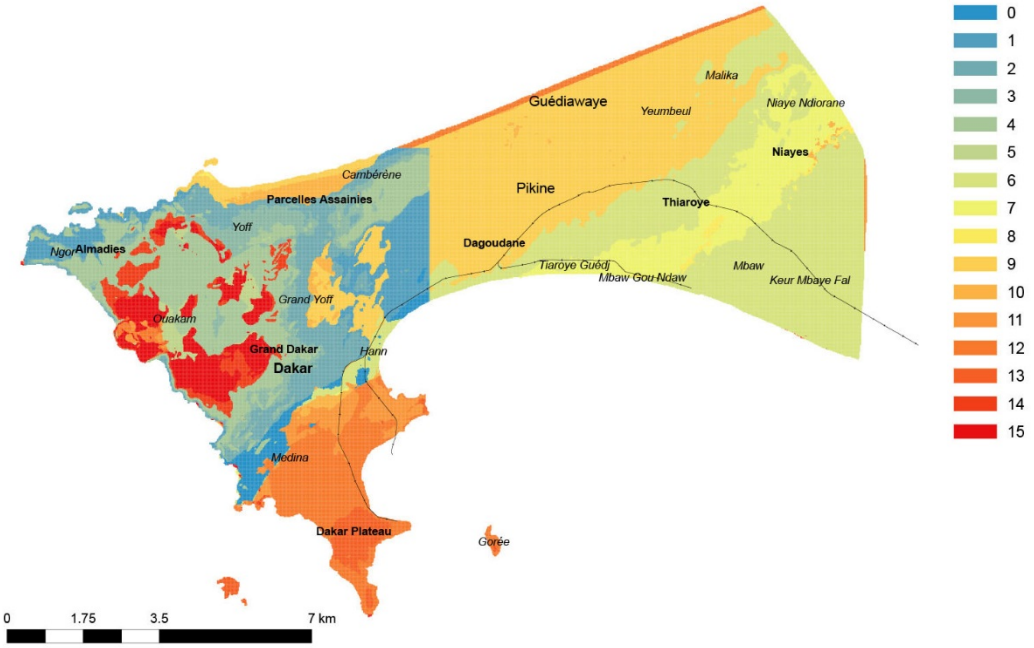

Figure 8. Distribution of the indexes of the one-dimensional SOM algorithm, which identified sixteen distinct patterns of combined resource potentials and allows to more easily capture the differences between resource combinations.

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 (Figure 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 meters, mid-range geomaterial potential at all depths, low groundwater potential and low to medium geothermal potential. This suggests that Dakar-Plateau and places like it (indexed by the same node) are good candidates for shallow to deep underground construction and 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 (Figure 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 meters. 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 to use 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 yet, 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, then 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 city authorities 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. Conclusion: 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 sustainable fashion. As the maps produced by the study show, the city is characterized by zones of different combinations of resource potentials from the surface to 45 meters deep. Of course, the evaluation presented here should be followed up with more detailed local investigations. It provides only 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, independent of measure. Further testing is needed, of course, to explore the limits of this approach.

Every city should take stock of its underground resources—even if the result is protection rather than exploitation, prevention rather than intervention. The mapping method proposed here provides a strategy for cities to gain a quick overview of their resource potentials, without needing a large amount of data. In principle, more data is better, but this poses challenges in practice. As the number of criteria increases, so does the difficulty of establishing the relationship between them. Where only one resource potential (or a predetermined combination of potentials) is of interest, multi-criteria decision-making methods like 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 their maximum. The study presented here is only a first step to confront 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 a concern for the ability of urban planning in general to respond to increasing amounts of multidimensional spatial information.

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