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Combined Districting and Main Line Routing—A Method to Implement a Basic Drinking Water Supply Infrastructure in Informal Settlements

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Abstract: The upgrading of large informal settlement areas takes place in sections for technical, economic and social reasons. On one hand, planning is faced with the challenge of taking individual structural and social conditions into account when dividing up the districts. On the other hand, the routing of the mains of a pipe-based infrastructure (water supply) must be selected in the context of the entire area under consideration and integrated into a superordinate network layout. In this paper, a method that combines these contrasting approaches is presented. Potential district boundaries are identified based on existing infrastructure and development patterns, as well as considering the routing requirements of a piped drinking water supply. Thereby, social factors can be considered in the decision-making process. Subsequently, an area subdivision is performed by a recursive partitioning algorithm. The choice and combination of different compactness measures influence the shape of the districts and, thus, the spatial organization. The geodetic height is integrated into the algorithm via an admissibility condition, so that the subsequent development of a district can take place via one pressure zone. By means of variations in the input parameters of the zoning, different planning levels can be generated, which finally lead successively to the upgrading of an informal settlement area.

Keywords: water distribution systems; slum upgrade; basic infrastructure; planning support; districting; sustainability

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1. Introduction

Rising populations combined with ongoing urbanization pose major challenges in terms of providing for the population and introducing new infrastructure and services, particularly for cities in developing and emerging countries. The world's fastest-growing cities are in Africa, Latin America and the Caribbean and Asia, where urban populations are projected to increase by about 20% (Africa), 10% (Latin America and the Caribbean) and 10% (Asia) by 2030 (reference year 2018) [1]. The reasons for the emergence and development of informal settlements are manifold and are not part of this paper. Currently, more than 1 billion people live in slums or informal settlements [2].

Informal settlement areas often have high population and building densities combined with low living standards. For decades, numerous approaches have existed to upgrade these areas [3]. The challenge in introducing infrastructures is to find suitable routing options in the mostly unmapped, unstructured and densely populated areas. History has shown that the resettlement measures required for this are very complex, expensive and are often not accepted by the affected population (for numerous reasons, mainly due to the disruption of social networks, loss of income opportunities, dissatisfaction with compensation, etc.) [4,5]. In addition to the structural heterogeneity, there are also social, cultural, ethnological and economic differences as well as socio-spatial relationships within the settlements that must be considered in the planning process [6]. Even today, ongoing debates exist on the most suitable method and which required objectives are best for an upgrade [6]. The trend is leaning towards a step-by-step upgrade of individual settlement areas with the involvement of the population. The step-by-step upgrade offers a more tailored consideration of the possible requirements. However, upgrading large informal settlement areas is usually impossible due to manpower and financial reasons. A predetermined, final planning for the entire area under consideration is also not beneficial, since structural changes can occur within the informal settlement during the necessary construction phases, which could take up to several years. This is due to the high fluctuation in these areas. Depending on the work location, family circumstances, etc., it is not unusual for people within a settlement to leave their respective settlements and move to other locations. It is also not uncommon for settlements to become more densely populated as a result of a sustained influx. As a result, the settlement structure on which the planning is based may no longer exist when construction begins. The focus of today's upgrading approaches is therefore on a step-by-step development strategy based on physical plans, the involvement of the population and the conversion/redesign of areas [7]. As a result, the settlement area is divided into individual districts, called upgrading areas. The division of large areas into smaller subunits has advantages for planning, since the complexity is usually reduced and the implementation of the measure is favored from a logistical and financial point of view. In the context of a participatory upgrading approach, the decision-making process is also simplified based on a smaller group of stakeholders. Moreover, this approach allows the identification of priority areas for intervention based on the population's livelihood (e.g., health) and characterized by the amount of time and impact an upgrade has to offer [8]. However, before the improvement of an upgrading area can take place, it must be ensured that this area can also be tapped and supplied. With regard to the various services, the provision of clean drinking water in particular plays a central role. According to the Sustainable Development Goals of the United Nations, everyone has the right to access clean drinking water (SDG 6: Ensure availability and sustainable management of water and sanitation for all) (it must be noted that despite some progress, this goal is still unachieved in many places [2]). In the case of a piped water supply, the water must be transported to an intake point on the edge of the district under consideration. From this point, the water can easily be distributed in the district. Therefore, for the anticipatory planning of large informal areas, there must be a superordinate network of main pipelines connecting each upgrading area to a water source (e.g., possible connection to a network of a formal settlement area or connection to a reservoir).

In the following sections, a new method is presented in which a superordinate network layout of main pipelines is derived from the districting for upgrading areas. Through the interaction of network creation and area division, districts are integrated into a superordinate layout so that flexibility is increased with respect to future development activities. The approach to determining a route area for potential main pipelines is first defined based on the actual existing settlement structure and terrain topology. Subsequently, smaller subunits, called basic areas, are then derived. The area division is done from a technical point of view, using a recursive partitioning algorithm following Kalcsics et al. [9]. Due to its modularity, the algorithm allows the consideration of different criteria and parameters that influence the spatial organization and water supply. To avoid multiple pressure zones in the respective upgrading areas, the geodetic heights are considered during the area partitioning as an admissibility condition.

The paper is divided into six sections. Section 2 discusses a short review of the state of the art. The structure of the method, the software and the data used are found in Section 3. The method starts with the creation of a maximum network of potential main routes and derivation of the basic areas considering various constraints. The basic areas are then combined into districts using a recursive partitioning algorithm. In this step, user-specific criteria for spatial organization as well as constraints for hydraulics in each district can be considered. Based on a case study of a large informal settlement area of a real city, the results are presented in Section 4 and discussed in Section 5. The paper culminates with a conclusion in Section 6.

2. State of the Art

The division of an entire area into individual upgrading areas results in an interdisciplinary problem. On the one hand, an optimal division of the area should be made with regard to the parameters to be selected, such as shape and size. On the other hand, social, cultural, ethnological and technical boundary conditions must also be taken into account in the formation of upgrading areas. The method in Section 3 combines a wide variety of disciplines, a brief overview of which is given below.

2.1. Upgrading Areas in Informal Settlements

There is no uniform or fixed definition for the term informal settlement. The United Nations [10] defined the term in two different ways: "1. Areas where groups of housing units have been constructed on land that the occupants have no legal claim to, or occupy illegally" and "2. Unplanned settlements and areas where housing is not in compliance with current planning and building regulations (unauthorized housing)". Park [11] defined them as "Houses (for temporary or permanent use) which have been built on land without formal planning approval". Here, it refers to settlement areas that were founded haphazardly and without land ownership or illegally in the context of urbanization and population growth. As a rule, development takes place without consideration of formal specifications. In this paper, the term is used synonymously with the term slum, which, according to UN-Habitat [12], settlement areas are determined to be if they meet any of the following criteria:

- Insecure residence status;
- Inadequate access to safe water;
- Inadequate access to sanitation and other infrastructure;
- Poor structural quality of housing;
- Overcrowding.

The blockwise upgrading of informal settlement areas is an approach that has been known for a long time [13]. Thus, dividing an informal settlement area into individual upgrading areas/upgrading blocks is now common practice in upgrading projects [14]. A block thereby describes a collection of adjacent shacks. Curdes [15] describes a block as a collection of parcels of land surrounded on all sides by streets. Upgrading blocks allows for the consideration of important socio-spatial relationships and strengthens community decision-making processes in a participatory planning approach [13]. For planning purposes, subdividing the overall area means reducing the solution space. In this paper, the term district (often used in territory planning) is used synonymously with the term block.

In an approach described by van Horen [16] for the upgrading of an informal settlement in Durban (South Africa), the individual blocks are demarcated from each other by existing streets/roadways, paths and footpaths. In this context, a distinction is made between fixed and flexible elements. Van Horen defines fixed elements as streets/roadways, paths, footpaths and public facilities. Flexible elements are defined as plot boundaries. The background to this distinction is that plot boundaries were not yet altered in the initial phases of the upgrade to allow for greater flexibility in property transfers and boundary adjustments between neighbors later on. The approach resulted in less than 1% of households having to be relocated as a delivery of basic services were introduced, leaving the settlement pattern largely unchanged [16].

Brelsford et al. [17] divided built-up, urban spaces into two categories according to access systems (streets, roads, paths) and places (buildings, public spaces). They highlight that access systems can be used to describe any city as an interconnected set of blocks. In this context, the blocks are surrounded by an infrastructure that, in the optimal case, mediates access to any place within the city [17]. In the case of informal settlements, this access is often not provided. To solve this access problem, Bresford et al. [17] developed a mathematical tool that considers minimum-cost restructuring and reblocking. From a technical perspective, reblocking refers to changing the topology of a settlement without changing its specific geometry. The resulting spaces provide access to roads and infrastructure.

In terms of mapping the areas, new approaches rely on the automated analysis of aerial photographs or remote sensing [18–20]. Today, daily updated aerial images can be generated with relatively little effort through the use of drones and subsequently be evaluated using readily available algorithms. The georeferencing of the data obtained from the aerial images facilitates their use in automated processes. The information obtained on the building structure as well as open spaces can be integrated into territory planning processes and, thus, also play an important role in districting.

2.2. Districting: Introduction and Basics

Districting refers to the grouping of smaller units (basic areas) into a specified number of larger units (districts or territories), taking into account relevant planning criteria. Very well-known examples can be found, among others, in the division of electoral districts (political districting), sales (sales territory design) and distribution territory planning (distribution districting), and service territory planning (service districting) [21]. While the goal of electoral districting is to give each vote an equal influence, the focus of sales districting is often on profit maximization or cost minimization. Furthermore, district planning can ensure that the associated workload is distributed evenly among the districts [22]. Districting is also used in the distribution of public services, such as the allocation of students to schools. Here, students can be optimally distributed while maintaining school capacity, minimizing commute times or ensuring a balanced ethnic composition [23–26]. When applied to police districts, low response times of the emergency forces can be achieved via districting [27,28]. Another area of application that has been studied is the splitting of a monopolistic built-up power grid into smaller areas in an attempt to promote competition in the power sector [29].

The planning criteria differ depending on the use case and thus have to be chosen specifically. The most often-used planning criteria are compactness, contiguity (connection), balance and a complete and unique assignment of all basic areas [21,30]. Geographically compact areas are, according to Kalcics et al. [9], "somewhat round-shaped and undistorted". A clear definition of compactness does not exist [23]. Furthermore, no generally valid, mathematical measure of the compactness can be defined [23,31]. Compactness is multidimensional and therefore subjective and can vary depending on the application. Compactness can refer to the whole area of interest (global compactness), (selected) individual areas (local compactness) or the combinations of both [23]. For example, the global compactness of an area can be determined by the lengths of the inner borders or the average compactness of the included areas. Numerous approaches have been developed to assess the compactness of a specific area. According to Ansolabehere et al. [32], the different approaches in the literature are differentiated into categories. They are subdivided into measures of dispersion that assess the general shape and area of a district, measures that assess the regularity of the perimeter of a district (poor assessment of districts with distorted boundaries; the maximum compact district is a circle) and measures that incorporate population distribution (inclusion of population concentration when assessing the shape of a district, e.g., in political applications). Young [31] presents several compactness measures in this regard, each with its advantages and disadvantages. Kaufman et al. [33] refer to the length–width ratio of the smallest enclosing rectangle, the convex hull ratio, the measures of Reock [34], Polsby–Popper [35] and a modified approach according to Boyce–Clark [36] as common compactness measures. The convex hull ratio describes the ratio of the area to the area of the minimum bounding convex polygon of the respective domains. On the other hand, the Reock and Polsby–Popper measures are circle-based measures. While Reock calculates the ratio of the area of a region to the area of the smallest circle enclosing the region, Polsby–Popper determines the ratio of the area of the region to the area of the circle with the same bounding circumference. The Boyce–Clark measure evaluates compactness using the normalized mean deviation of the lines leading from the centroid to the vertices of an area. In addition, Kaufman et al. [33] defined a new compactness measure, the X-symmetry. Compactness is determined by the quotient of the overlapping area of a district and its reflection on the horizontal axis, and its original district area [33]. In this way, shapes (such as circles and rectangles) receive good scores due to their symmetry. Ansolabehere et al. [32] describe the convex hull ratio and the Reock, Polsby–Popper, and Schwartzberg measures as “key methods” for measuring compactness. The Schwartzberg measure corresponds to the ratio of the circumference of the district boundary to the circumference of a circle of equal area [37]. In principle, the convex hull ratio and Reock’s measure can be classified as dispersion measures, whereas the Polsby–Popper and Schwartzberg measures evaluate the perimeter of the district and the course of the outer boundary, respectively. In terms of urban planning, high compactness means that individual units of a district are comparatively close to each other, so that there is an assumption that this will result in shorter distances or travel times within a district [28]. The same applies to contiguous areas [21]. They enable rapid travel without having to leave the area. Accordingly, high compactness together with the contiguity criterion indicates, on average, short distances within a district and are therefore key to minimizing travel times [38]. Applied to the implementation of a service such as piped water-supply infrastructure, a short distance means a correspondingly shorter pipe length. Thus, meeting the criteria has a positive impact on installation costs as well as hydraulic pipe resistance (and thus lower pumping energy costs).

Through the criterion of balance, an attempt is made to distribute a certain quantity, defined as an activity, evenly among the emerging districts. It corresponds to a property of the basic areas that varies depending on the planning scenario [9]. With respect to the division of sales and service districts, the activity can be expressed in terms of workload, work effort (for providing services), travel times, or potential profits. Moreover, other attributes such as area, consumption, population or even their ethnic composition [21] are expressed here. Usually, only one activity is considered within a districting problem. There are only a few publications in which several activities are included within the balance [21].

The criterion of complete and unique assignment means that all basic areas must be represented in the solution. In addition, a basic area can only be assigned to one district. Multiple assignments here are not possible.

Numerous methods exist for solving districting problems. These methods can be grouped into different classes. Kalcsics and Ríos-Mercado [21] distinguish between location–allocation methods (heuristics), construction methods, set-partitioning models, computational geometry methods, and meta-heuristics. More detailed descriptions are given in Ricca et al. [39]. The recursive partitioning algorithm used in this paper, following Kalcsics et al. [9], is from Computational Geometry Methods [21]. The algorithm uses the principle of successive dichotomies. This means that an iterative partitioning of the planning domain is regulated into two parts at a time. The geometrically motivated method leads to very good results with respect to the balance of the planning area [23]. Thus, a good partition of the chosen activity criterion is expected. Based on the recursive partitioning algorithm, Ulrich developed [40] a more advanced heuristic for combined site and area planning. Butsch [23] also examines the strengths and weaknesses of the algorithm in his work and developed it further. Furthermore, he developed another algorithm and concluded that both algorithms can also be solution approaches for route planning or site selection (“Moreover, these algorithms can be a basis of solution approaches where districting problems occur as part of another problem, such as routing or facility location” [23]). In addition, the interactive usability of the algorithm is emphasized, which can be well adapted to the respective problem via its modular structure and can be utilized as a good consideration for different planning criteria [21,23]. The algorithm delivers fast results, even for very large solution spaces, and fulfills the criterion of contiguity by dividing the area along separation lines. The general operation of the algorithm, as well as the specific adaptations made for this paper, is given in Section 3.3.

3. Materials and Methods

In this section, a method for dividing an informal settlement area into individual upgrading areas (hereafter referred to as districts) from a water supply perspective is presented. The idea of the method is to identify a superordinate main pipeline layout for a pipe-based water supply, which provides the possibility to divide the area into upgrading areas considering spatial, social and technical criteria. The network layout of the main pipelines will later enable the development of the individual districts in the course of future upgrading measures. It is taken into account that future intake points are not known due to the high fluctuation in informal settlements and the related changes in the settlement structure. The partitioning can be done manually based on the identified potential pipeline routes or automated using a recursive partitioning algorithm following Kalcsics et al. [9]. The proposed partitioning can also be subsequently customized, ensuring maximum flexibility to prevailing conditions.

The structure of the method is shown in Figure 1. To distinguish between a higher-level network layout and a single upgrading measure, different levels of scale are introduced. Abbott [13] defines four levels. The first and highest level deals with the integration of the informal into the formal settlement area. The second level covers the informal settlement as a whole. The third level is referred to and compared to that of the small neighborhood, which has its roots in the block concept. The fourth and lowest level focuses on each family or the residents living in the informal settlement area. Similar subdivisions have been conducted by other researchers. Kohli et al. [18] categorized these into slum environment, slum settlement level, and object level. Taubenböck and Kraff [41] defined the spatial levels for a systematic structural analysis into entire district level, block level and building level. Hecht [42] differentiates the automated classification of building floor plans of the spatial levels in terms of a macro level, meso level and micro level, which Arlt et al. [43] defined as spatial scale levels of the settlement structure and related them to scales. The integration of the informal area into the surrounding formal settlement is not part of this paper. Following these subdivisions and considering designations in districting, the designations of the levels of consideration are classified into informal settlement level, district level and building level. The assignment of properties to each level are not so strictly divided in this paper. Building on each other, the method progresses through these levels, with the level of planning detail increasing steadily. The focus of this paper is on the formation of the district level, which can be described as a subdivision of the superordinate informal settlement level.

At the first and highest level, defined as the informal settlement level, the area under consideration is delineated and the existing infrastructure and respective buildings, as well as impassable barriers and open spaces not available for routing, are mapped in a GIS system. The data provide the basis for the creation of a maximum network according to Mosbach et al. [44]. The maximum network initially contains all potential pipeline routes. By defining a minimum width for main pipelines and removing all branches, the maximum network is reduced. The remaining main pipelines form a meshed ring network. The settlement area lying within a mesh is defined as the basic area. In the following level, the district level, the districting of the upgrading areas takes place. For this purpose, the basic areas are automatically grouped into individual upgrading areas by the recursive partitioning algorithm, taking the geodetic height, the spatial criteria and, if necessary, the social criteria into account. The recursive partitioning algorithm is a geometry-based method that, unlike classical methods of area partitioning, does not require a special solver. Thus, it can be applied to other study areas without adaptation.

At the lowest level, the building level, an optimized routing of the water supply network is created for each district, taking the maximum network, based on criteria to be defined (e.g., connection rate, max. distance to standpipe/home connection, personal water demand), into account. This level is described in detail in Mosbach et al. [44] and is therefore not discussed in this paper.

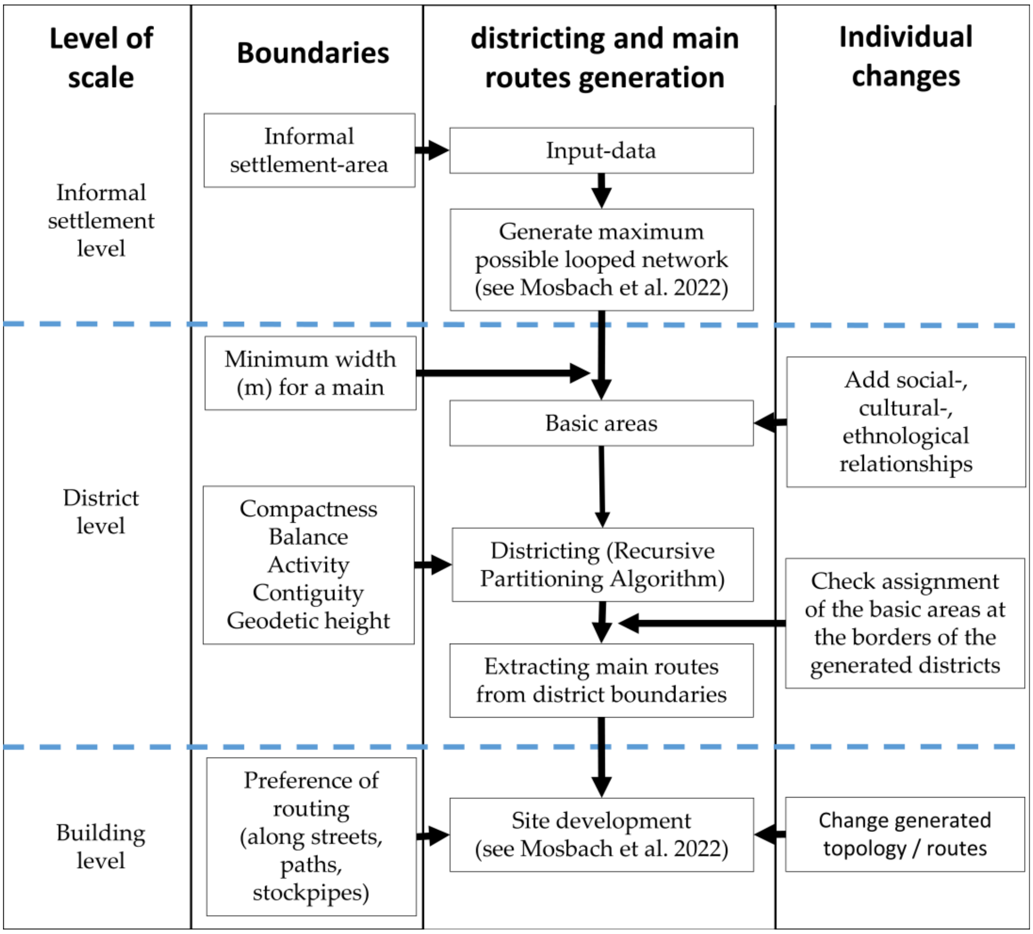


Figure 1. Overview and structure of the method [44].

The following exemplary goals are defined for the study area presented below:

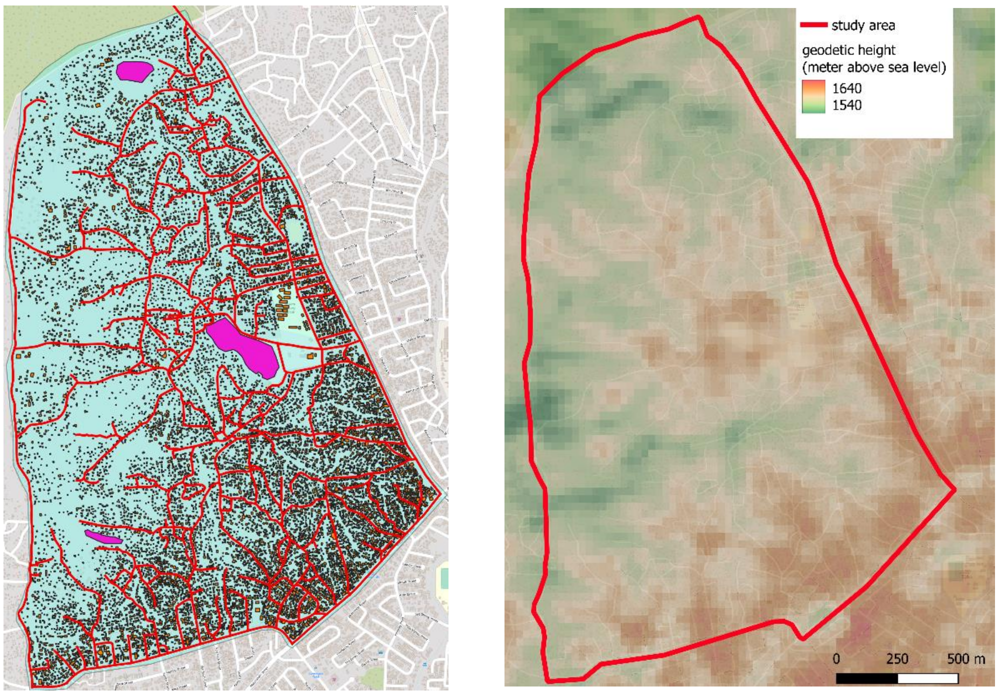
- A superordinate main pipeline layout for a pipe-based water supply is searched.
- The routing should run along existing roads/trails or between houses that are at least 10 m apart from each other.
- The individual districts should approximately be equal in size (area).
- Geographical compactness. Compactness makes the districts easier to manage and economical to operate [9] so that pipeline lengths are mostly minimized.
- Elevation compactness (to prevent multiple pressure zones within a district).

3.1. Software and Data

For the implementation of the method, only free open-source software is used. This has the advantage that individual adaptations regarding data integration and intersection as well as changes of upgrading targets can be implemented quickly. The method is implemented in the programming language Python. The recursive partitioning algorithm was also implemented in Python following Kalcsics et al. [9]. The GIS system used is the open-source program QGIS [45]. By integrating QGIS into the Python environment, all QGIS tools can be used to analyze and intersect the data from within the programming environment. The maximum and main pipeline network are then modeled with approaches from graph theory using the Python package NetworkX [46]. The dataset used to illustrate the method contains the built-up area in the form of georeferenced polygons and roads/paths as line vectors (accessed on 29 March 2022). The data are from OpenStreetMaps [47] and are therefore freely available. The digital elevation model (DEM) is from NASA Earthdata [48] and is also freely available. The resolution of 30 $\times$ 30 m is sufficient for the explanation of the method, but for more detailed hydraulic investigations, a finer resolution is recommended.

3.2. Informal Settlement Level: Area under Consideration, Data Import and Maximum Network Creation

The first step is to delineate the area of interest identified as informally populated and import the available data into QGIS. Impassable barriers and, thus, space not available for main routes are imported into QGIS in the form of polygons and/or line vectors, or are subsequently digitized from aerial photographs. These spaces are referred to as barriers. Barriers are defined as rivers, floodplains, steep slopes, railroad tracks, multi-lane highways, subsoil conditions, etc. Since no precise information on barriers is available for the demonstration area, these are only integrated as examples in the form of polygons for demonstration purposes. The result of this layer is shown in Figure 2a. The area under consideration includes about 11,900 shacks (orange) in an area of about 3.77 km^2 (cyan). The areas marked as barriers are shown in magenta. In Figure 2b, the elevation data used are shown as a 30 × 30 m grid and colored according to the elevation value. The study area has a maximum elevation difference of 63 m (min 1546 m above sea level, max 1609 m above sea level) based on the supply points (shacks). Assuming that a supply zone may have a maximum elevation difference of 50 m (assuming maximum design pressure 10 bar, 3 bar water pressure at the transfer point, 2 bar reserve for water hammer), it follows that the geodetic elevation must be taken into account when creating the district level to prevent multiple pressure zones in an upgrading area. This is accounted for in the recursive partitioning algorithm in the form of a parameter for a maximum allowable elevation difference. In principle, the hydraulic requirements and specifications have to be selected individually.



(**a**) (**b**)

Figure 2. Study area as well as input data (**a**) (source map/shacks/roads: [47]); DEM map of the study area (**b**) (data: [48]).

Possible district boundaries must be identified in advance for the subsequent subdivision of the study area. At the same time, it is typical for informal settlements to have services such as water, wastewater, sanitation, garbage collection and electricity running along existing roads or on the outer sides of a settlement block [17]. Therefore, in subdividing the area under consideration, only district boundaries that have sufficient space to introduce infrastructure are considered. The potential district boundaries thus correspond to the potential main routes for infrastructure. In this paper, these are the main pipelines for a future pipe-based water supply.

A maximum network (i.e., all possible routes) is determined based on the development pattern, already-mapped roads/trails, existing pipelines and designated barriers (areas that cannot be developed). As described in Mair et al. [49] and Rehm et al. [50], the concept of parallel infrastructures is applied to identify possible routing options, which, according to the approach of van Horen [16], are defined as fixed or unchangeable. Based on the development, additional open areas that are also available for potential routes are identified. The method does not include any resettlement measures, so the location of shacks in the area is taken as a given. Only the previously defined barriers are excluded from consideration. For the selected demonstration area, the building footprints are available in the form of georeferenced, two-dimensional polygons in freely available OpenStreetMaps data. Based on the two-dimensional building geometry and considering the previously defined barriers, Voronoi regions are formed for each object. Voronoi polygons originate from algorithmic geometry and are used to model space [51]. The medial axis delimiting the Voronoi regions from each other is called the Voronoi edge and represents the potential path. For details on the generation of the maximum possible network, see Mosbach et al. [44]. The maximum possible network is reduced according to the requirements for a higher-level water supply main pipeline layout. Requirements for the implementation of the construction measure, such as the working strip width (minimum width of the trench, dumping of the excavated material for backfilling, accessibility for construction vehicles, etc.) have to be considered. Even after the construction work, restrictions on use in the area of the pipeline are agreed by means of a protective strip with a corresponding minimum width. The requirements for a minimum width of the protective and working strips result from the respective regulations and must therefore be selected on a country-specific basis. However, it must be kept in mind that in informal settlements areas, often more pragmatic solutions with significantly smaller minimum widths are chosen. If a route is also to be used for other infrastructures (e.g., the introduction of a road network), the minimum width must be selected according to the infrastructure with the largest space requirement, or corresponding requirements must be taken into account for parallel runs. The multiple use of a route is a useful way of dividing the district level, as it allows other infrastructure to be taken into account and thus reduces the total costs of a construction measure. The maximum possible network determined in the first step is therefore reduced according to the actual space conditions and requirements. Routes that do not meet a predefined minimum distance to a building and/or barrier are discarded. The minimum allowable distance is defined by a distance buffer. If the buffer intersects a building/barrier, the corresponding path is discarded. In this way, possible routes for main pipelines become visible. In order to ensure maximum flexibility for future upgrading measures with regard to the development of a district, all districts should be surrounded by main pipelines, similar to the approach of van Horen [16]. In this way, it is not yet necessary to determine the locations of possible intake points into the districts. At the same time, the provision of basic service along the district boundaries is made possible before the actual upgrading. For this reason, the remaining branches, even if they would be eligible for a main pipeline according to the buffer, will be removed. A maximum meshed ring network of potential main pipelines is created. The areas surrounded by the main pipelines are hereafter referred to as basic areas. If social relationships exist between individuals of adjacent basic areas, the basic areas can be combined by removing the potential district boundary separating them. This ensures that, for example, members of a family are not later divided into separate upgrading areas. The steps from the initial situation to the generation of the maximum possible network to the derivation of the potential main pipelines and district boundaries are illustrated in Figure 3. The shacks are represented as polygons (orange), and the maximum possible network (blue) as well as the district boundaries (red) are represented as line elements. Basically, the tight coupling of the method to QGIS offers the possibility to intervene individually in the process at any time.

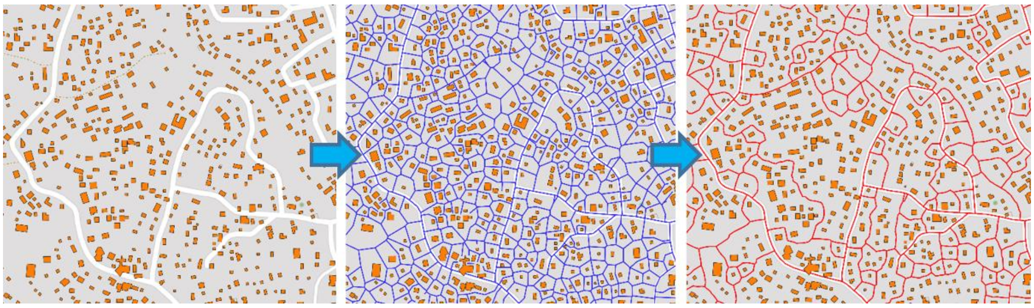


Figure 3. Generation of potential district boundaries and derivation of basic areas (basemap/buildings/polygons: [47]).

3.3. District Level: Districting

The generated basic areas are grouped and divided into a desired number of districts (blocks) in terms of area planning. Thus, a district consists of a set of basic areas. In addition to the technical/geometric constraints presented in the informal settlement level, social, ethnological and economic constraints must also be considered in the blockwise upgrading of settlement areas. Due to the close coupling of the method to QGIS, neighboring basic areas can be merged for this purpose before zoning, so that they are located in the same upgrading area later on. However, the use of personal data is subject to the consent of the data subjects. For this reason, the districting in this publication is based solely on geometric/geographic information from OpenStreetMaps. While the aggregation of basic areas into districts in QGIS is also manually possible, taking individual criteria into account, a procedure for automated district creation is presented. The challenge is that very large areas with many elements to be classified lead to very large combinatorial problems. Using classical approaches (e.g., location–allocation) results in very large solution spaces and thus very long computation times [9]. The recursive partitioning algorithm used here exploits the underlying geometric information and produces results in an acceptable computation time, even for very large solution spaces. The following section contains the general operation of the algorithm. For further details and a discussion of the general operation, see Kalcsics et al. [9] and Ulrich [40].

At the outset, the district planning problem consists of a set of basic areas $B = \{1, \ldots, n\}$, each representing a geometric object in the plane, and the desired number of districts $q \in \mathbb{N}^+$. The algorithm divides the problem P(B,q) into smaller sub-problems P′ until the desired district number is reached (i.e., a sub-problem P′ consists of only one district P′(B,1)). Here, each basic area has planning-relevant properties (specific activity) that must be taken into account when aggregating the basic areas. In order to generate an optimal partition, each sub-problem is divided into partitions using partition lines, which are then evaluated and compared based on various criteria. Partitioning an area along partition lines implies contiguous districts. The partition lines are offset from each other by an angle of 180°/n in the planning space, where n corresponds to the number of search directions specified by the user. In this way, the number of search directions affects the combinatorial complexity, influencing the runtime of the algorithm. At the same time, this means that a small number of search directions in interaction with the spatial distribution of the basic areas have an influence on the achievable compactness and can thus have a negative impact on the quality of the results [39]. Kalcsics et al. [9] reached desirable results with n = 8, while Ulrich [40] recommends only four search directions in his application. The separating lines resulting from the search directions divides the problem into two halves. These are called the left (B_l) and right (B_r) sides of a partition. For a partition $P = (B_l, B_r)$ of a point set B, $B_l, B_r \neq \emptyset$, $B_l \cup B_r = B$, $B_l \cap B_r = \emptyset$. The division of the basic areas is based on the balance criterion. For this purpose, the sum of the activities is determined first.

This should be divided as equally as possible between the two districts to be formed. In parallel, the basic areas are sorted according to the search direction. From the sorted list, basic areas are continuously assigned to a district until the admissible activity of the district is reached. In a subsequent admissibility check, a tolerance or deviation of the balance can be considered. This is essential, especially for discrete problems, since an exact division of the activity is often not possible. If a partition is admissible, the resulting partition is evaluated based on various criteria. In this paper, the evaluation is based on compactness and contiguity. The partition with the greatest compactness is selected. The procedure is repeated until the desired number of districts is reached or each sub-problem has only one district to be defined ($q' = 1$). If, during runtime, a given sub-problem cannot be partitioned into an admissible partition using the possible search directions, a backtracking function is triggered. A problem that has produced a sub-problem that can only be solved impermissibly is reactivated, the existing partition is deleted and the program continues with another partition according to the sorting of the evaluation measure (here, the compactness measure). The search direction that led to the invalid sub-problem is also deleted for the reactivated problem in order to exclude a repetition of the invalid partition. In the case that a problem no longer has valid search directions, it is also considered to be solvable only improperly and triggers a backtracking event for the parent problem.

The modular structure of the algorithm allows the integration of water supply-specific criteria. For this purpose, the described algorithm was adapted accordingly. The maximum network forms the basis for defining the basic areas (see Section 3.2). Depending on whether there is enough space around a shack for a main pipeline or not, basic areas consist of one or a collection of several shacks. The classification of a basic area into the respective partition is done by a point geometry (i.e., the geometric center of gravity). If a basic area contains several shacks, their properties (activity) are combined (summed) and assigned to the geometric centroid of the basic area. The representation of basic areas in the form of a point in the plane is a typical approach to the division of service districts [23,38]. It must be kept in mind that the geometric centroid may lie outside the object in the case of branching concave bounded areas. Therefore, an automated check of the basic areas and their geometric centroids identifies appropriate areas so that the user can react to them. Furthermore, difficulties arise with respect to checking the contiguity criterion when points are considered. For this reason, the basic area polygons are connected to their corresponding centroids by an internal ID. If the points assigned to a partition result in a contiguous district needing to be checked, the associated basic areas are determined via the IDs. These are then examined for common edges (external boundaries). The admissibility of a partition is also checked via the balance. Depending on the available information, any numerical quantity can theoretically be considered via the balance. In terms of water supply, this includes the water demand, population size or the supplied area. Since the present case is a discrete optimization problem, it is unlikely to satisfy the balance criterion without deviation. For this reason, a tolerance range is defined for the balance, within which a deviation between the individual districts is allowed. With regard to the hydraulic conditions within the districts, the terrain topology must also be considered in the area planning. In the interest of simplifying operations as much as possible, the pipelines in a district should be located within one pressure zone. Therefore, the geodetic elevation of the basic areas is incorporated into the permissibility review in the form of a hard termination condition. Since a basic area can also consist of a collection of shacks, the absolute high and low points of the shacks in the basic area are calculated and passed to the centroid as an attribute. The user can then choose which height difference is permissible within a district. If the permissible height difference is exceeded, the partition is discarded or backtracking is triggered. If a partition meets all admissibility conditions, the evaluation of a partition is done via compactness. As described in Section 2.2, different approaches exist to determine the compactness of an area. Currently, the approaches according to Reock and the convex hull ratio (from the category of dispersion measures), as well as the approaches according to Schwartzberg and Polsby–Popper (from the category of perimeter measures) are integrated. Additionally, the length–width ratio and the X-symmetry measure are also integrated. Since each of these measures rewards or penalizes certain area shapes (e.g., the convex hull a triangle, Reock a circle), Ansolabehere et al. [32] propose a combination of the measures. In terms of dividing the overall area into individual upgrading areas or districts, the areas should be as compact as possible for future development (assuming shorter distances and thus less required pipeline length as a result of compact areas), thus requiring the consideration of dispersion measures. At the same time, district boundaries correspond to future major routes, so measures that affect the perimeter of a district must also be considered. The method, therefore, includes the possibility to combine several compactness measures via weighting factors. In this way, the weaknesses of the individual compactness measures as described in Young [31] are counteracted. In this case, the overall compactness is calculated from the sum of the weighted individual compactness measures (i.e., it is a sum-based compactness measure).

4. Results

The potential district boundaries or main pipeline routes are composed of the already-mapped roads (concept of parallel infrastructures [49,50]) as well as the open areas identified on the basis of the built-up area and obstacles [44] (Section 3.2). Depending on the selected minimum distance to buildings or the minimum width of the protective and working strips, the identified open spaces result in different potential main routes and, thus, basic areas. The smaller the selected minimum distance, the more potential routing options are available. As a result, the number of basic areas also increases, favoring a more even distribution of the activity measure. Existing roads are taken as given and unchanged, according to van Horen [16]. Dead-end streets that cannot be used to form a basic area are disregarded. Figure 4a shows the study area with 11,900 shacks (orange). It is clear that the density of development is much higher to the southeast (near the formal area) than in the northwestern area. In Figure 4b, the minimum distance to development for routes over open spaces is $\geq$5 m. The existing roads that contribute to the formation of the basic areas are highlighted in black. In total, the area contains 5229 basic areas, the largest of which possesses 251 shacks. As a result of the less densely populated northwestern settlement area, many small basic areas are created, while fewer and larger basic areas are created in the densely populated areas. This effect becomes clearer when the minimum distance to the built-up areas is raised to $\geq$10 m (Figure 4c). In this variant, the study area contains 1637 basic areas. Particularly in the southeastern area, relatively large basic areas are created, which are only delimited by the already existing roads. The largest basic area contains 401 shacks. Depending on the planning approach, the basic areas may be too large to be defined as a single upgrading area and to be upgraded as part of an upgrading effort.

Another criterion is the desired number of upgrading areas. This has a direct effect on the goal of the area subdivision. If the goal is to obtain finished upgrading areas, the number of districts must be chosen according to the balance criterion (e.g., area, number of people) and in the context of the total area. If a large number of districts are chosen, smaller districts will be generated. Another possibility is to use the method to introduce an initial basic (infra)structure into a large area, from which further expansion can take place in the future. Taking into account the desired spatial organization, a correspondingly smaller number of districts should be selected. Based on the basic (infra)structure, further subdivision can subsequently be done using the method. In this paper, a superordinate main pipeline network is to be generated from the area subdivision. For this purpose, the total area is divided into 10 districts. The district boundaries thereby result in the routing of the main pipelines.

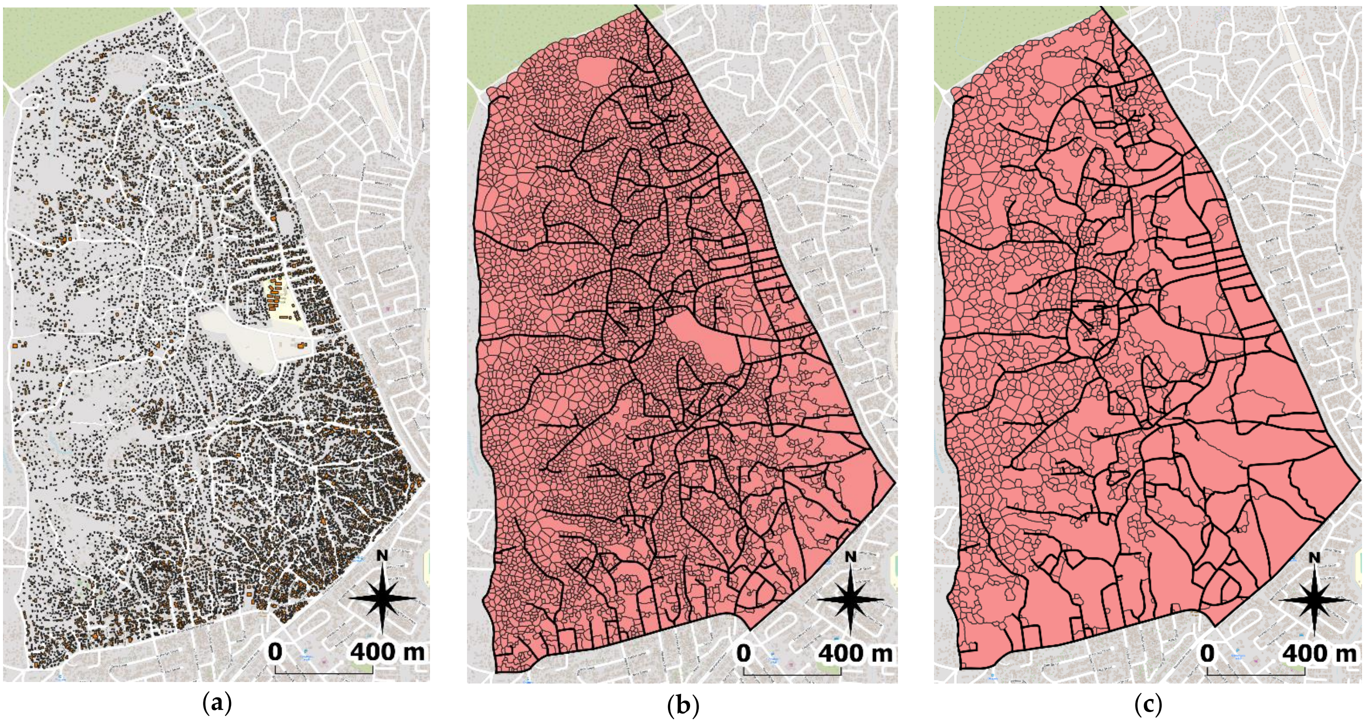


Figure 4. Area of interest (**a**); basic area creation at minimum distance >5 m (**b**); basic area creation at minimum distance >10 m (**c**) (basemap/buildings/polygons: [47]).

Figure 5 shows an extract of the results using different compactness measures. Due to the constraints regarding personal (social and socioeconomic) data in publications, the area is chosen as the balance criterion. In the admissibility condition, a maximum height difference per district of Δh = 50 m and a deviation of the balance criterion of 10% are accepted. The search directions of n = 8 are chosen according to Kalcsics et al. [9]. Depending on the chosen compactness measure, different spatial organizations and district shapes are created. In all divisions, the admissibility condition of height is fulfilled. In this example, the measures according to Schwartzberg (Figure 5a) and Polsby–Popper (Figure 5b) generate identical divisions, and thus confirm the established similarity of the two measures [32,35]. Interestingly, the measures according to Schwartzberg, Polsby–Popper, the convex hull ratio (Figure 5c) and Reock (Figure 5d) divide the southern part of the area under consideration very similarly. In contrast, the measures according to the length–width ratio (Figure 5e) and the X-symmetry (Figure 5f) create relatively independent forms. Significant differences arise in the northern area. Here, the measures according to Schwartzberg, Polsby–Popper and the convex hull ratio lead to acute triangular shapes, while the other measures cause rectangular subdivisions. In all subdivisions, a narrow, elongated basic area projects from the adjacent district to the northern portion of the district shown in black. This is due to the division of basic areas based on their centroid. Thus, the centroid of the narrow, elongated basic area sits in the border between the two districts. The southern areas are relatively large, so part of the area closes north to the neighboring district, while their centroid is further south. Such special assignment problems have to be corrected manually afterwards.

The compactness scale under the respective area classification enables a comparison of the districts formed by the respective compactness measure. Since no universally applicable mathematical measure exists to evaluate compactness [23,31], the results of the different compactness measures cannot be compared directly. In the current use case, an evaluation of the results could be done based on the length of the district boundaries. This corresponds to the length of the main pipelines and is thus directly related to the cost of implementing this infrastructure. Accordingly, the goal of districting would be to minimize the district boundary length. However, such a perimeter-based assessment would not take into account the respective district shape. For this reason, the results are visually evaluated similarly to Young [31]. This intuitive evaluation is based on personal opinion and can therefore be very subjective. Therefore, it is necessary to take the ideas of urban planning or spatial organization into account.

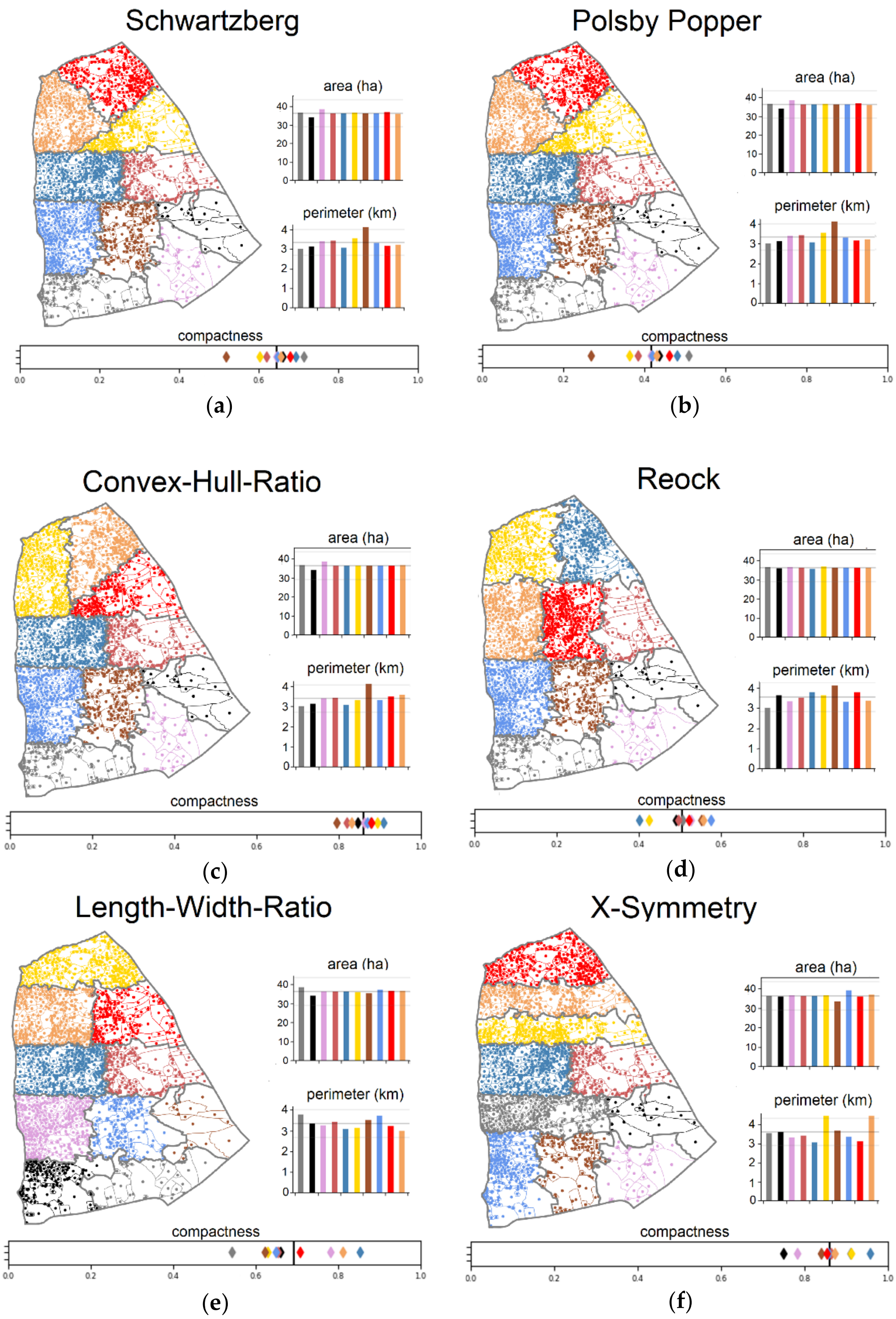


Figure 5. Results of area classification according to different compactness measures: Schwartzberg (**a**), Polsby Popper (**b**), Convex-Hull-Ration (**c**), Reock (**d**), Length-Width-Ratio (**e**), X-Symmetry (**f**).

If the minimum length of the inner district boundaries is used as an evaluation measure, the Schwartzberg classification with a length of 12.7 km shows the best results.

The X-symmetry, on the other hand, has the longest inner district boundaries with 14.1 km. However, if a triangular spatial arrangement, as formed according to Schwartzberg in the northern area, is not desired, it is possible to combine different compactness measures using weighting factors. Figure 6 depicts the combined measures according to Schwartzberg and the length–width ratio. As a result, the inner district boundary is reduced to 12.4 km and the triangular structure in the north changes to a rectangular spatial arrangement.

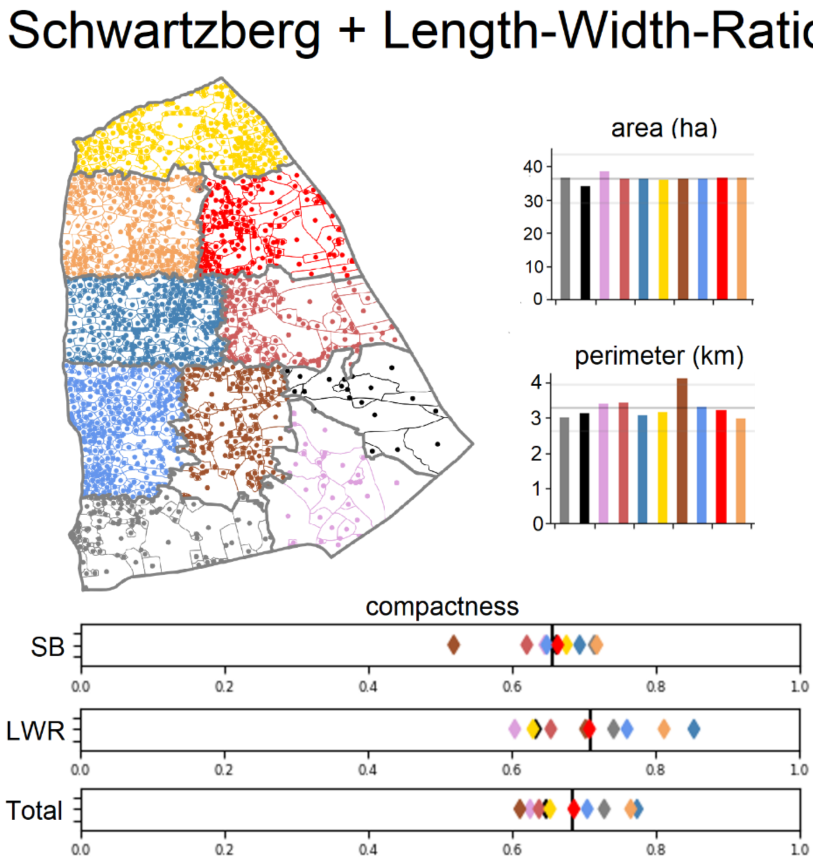


Figure 6. Area classification by weighted compactness measures.

As in the case of the narrow, elongated basic area that is projecting into the black district, the automatically generated results from a practical perspective should subsequently be checked and adjusted manually. This applies in particular to the boundary areas. Thus, the district boundaries are defined solely by the balance criterion and compactness measure, without giving preference to nearby streets or roads that would lend themselves as natural district boundaries. Therefore, it must be decided whether manual adjustments that may lead to a violation of the balance criterion will be made for each individual case. Such an adjustment is shown in Figure 7, where the district boundary is oriented to the existing road. Significant changes were only made for the center brown area, whose boundary course appeared to be very irregular as a result of the automated division. In total, about 3% of the basic areas were affected by a manual adjustment. These are depicted as the green areas in Figure 7 (left).

The final zoning is shown in Figure 8a. The division shows that some district boundaries run along existing roads/trails (shown in black), a situation that tends to favor development. As a result of the individual adjustments, the internal boundary length is reduced to 9.1 km. The height difference in the generated areas varies between Δh_{min} = 14 m (cream-colored area in the northwest) and Δh_{max} = 43 m (blue area). Based on this, the admissibility condition (max. 50 m) is fulfilled. Moreover, from a visual point of view, the area is divided relatively evenly and predominantly into the desired rectangular structure.

The main pipeline network derived on the basis of the district boundaries is shown in red in Figure 8b. While the alignment in the northern area has a somewhat curved course in its sections, it has a relatively straight course in the southern area. For a more direct course, either the allocation of the individual basic areas in the peripheral regions would have to be checked or resettlement measures would have to be considered.

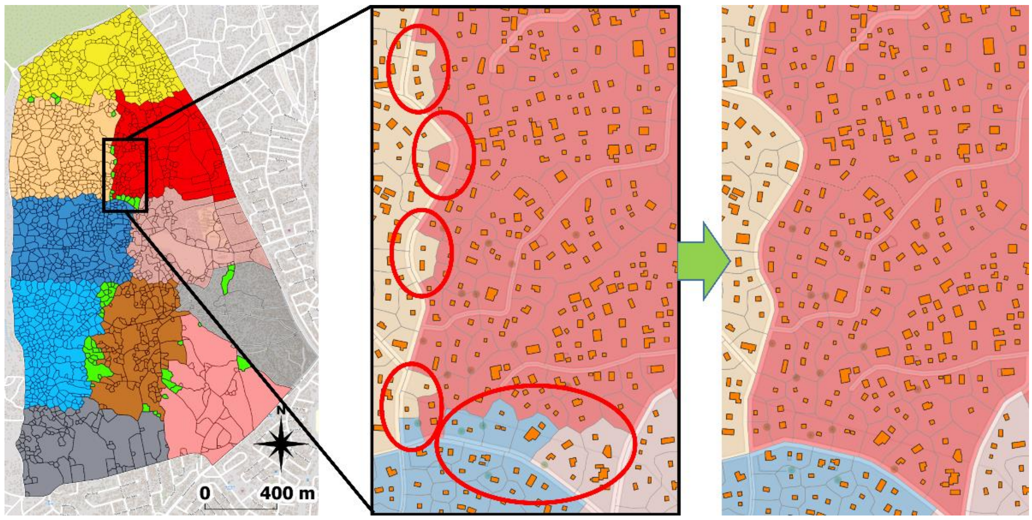
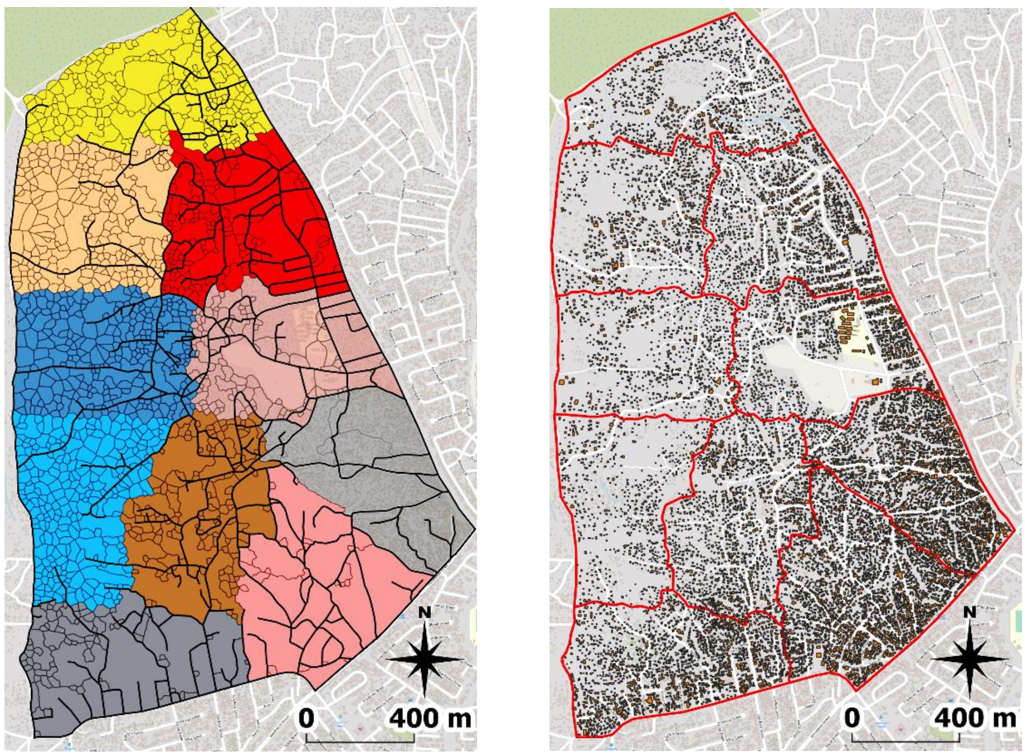


Figure 7. Manual adjustments after automated zoning (basemap/buildings/polygons: [47]).



(**a**) (**b**)

Figure 8. Final area division: colored districts (**a**); main pipeline routes for basic service provision (**b**) (basemap/buildings/polygons: [47]).

5. Discussion

The results show that through a combination of the method for maximum network generation according to Mosbach et al. [44] and the method for deriving basic areas presented in this paper, proposals for simultaneous area subdivision and routing of the main pipelines can be generated. The consideration of the available space in the delineation of the basic areas leads to the fact that the resulting district boundaries can simultaneously correspond to the routes of the future main pipelines. In this way, basic services can be provided in the outlying areas prior to the actual upgrading of a district, while at the same time, the routing provides maximum flexibility for intake points in conjunction with further developments. Providing basic services along the outer boundaries is consistent with common practice [17]. With respect to subsequent operations, the integration of geodetic elevation in the form of an admissibility condition results in districts that can be served through one pressure zone. This reduces the complexity of the water supply system and thus the cost. The main pipeline routes with the underlying DEM are shown in Figure 9. It can be seen that the districting considers the geodetic height, so that larger elevation differences (in this report, the maximum elevation difference is 50 m) are avoided in each district.

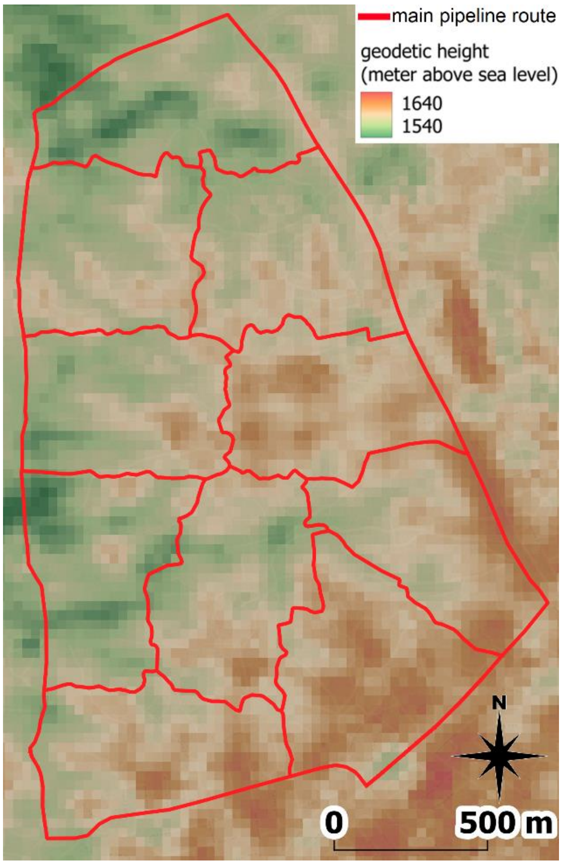


Figure 9. Final main pipeline route and DEM (DEM-data: [48]).

A weakness of this approach is that the routing within each district is not determined until the individual upgrades. Thus, in the early planning stages of districting, it is not yet known whether a route will actually run along the high and low points considered in districting. This means that the hard termination condition and thus the backtracking may be interpreted too strictly if the maximum geodetic height difference is violated. Moreover, with respect to the successive partitioning of the area by the recursive partitioning algorithm, it may be necessary to allow higher deviations for the balance criterion in case of large topological height differences. Nevertheless, the geodetic height must be taken into account for the area partitioning, since a violation of the maximum height difference makes the introduction of a pressure-based water supply more difficult from a hydraulic point of view.

Impassable barriers and, thus, space not available for potential pipeline routes are already taken into account when basic areas are created, so that they cannot be intersected by district boundaries/lines. However, they are not considered when aggregating basic areas into districts. Thus, conditions that naturally divide the space irregularly (e.g., rivers) [15] and lead to an individuality of the single areas are not considered. If such a natural obstacle (e.g., a river) crosses an area under consideration, the problem can be circumvented by performing a separate area division on both sides of the obstacle. Another possibility is to integrate the obstacle into the approach through an artificial basic area and assign it an artificial activity measure, corresponding to that of the targeted balance. In this way, the obstacle becomes its own (artificial) district.

The consideration of social, cultural, ethnological and economic criteria as well as spatial relationships is not explicitly dealt with in this paper. The reason for this is the constraints related to the publication of personal data. However, the method offers the possibility of integrating these into the zoning process by allowing neighboring basic areas to be appropriately merged prior to zoning. In this way, it is guaranteed that the affected residents are assigned to the same district after zoning, while the actual zoning is based on another spatial planning criterion (e.g., the area, number of shacks, etc.).

Due to the tight coupling of each step to QGIS, the area partitioning itself can either be done manually or largely automated by a recursive partitioning algorithm following Kalcsics et al. [9]. The algorithm provides very fast results and allows the generation of different planning variants. It contains common compactness measures that, on their own or weighted and in combination with the desired number of districts, influence the space organization in a user-specific way. However, as the results show, minor subsequent manual adjustments are recommended for fully automated districting. The successive divisions of the area allow it to be upgraded on the basis of successive planning levels. For informal areas that are in a constant state of change, the procedure offers a high degree of flexibility in order to be able to react to structural changes in the planning level. This is accompanied by a better overview of the required material and financial resources. In this paper, an initial basic structure was introduced into an unplanned area, which can be used as a starting point for further subdivisions. Alternatively, the resulting districts can be directly upgraded in the succeeding step, if desired.

6. Conclusions and Outlook

In this paper, a new method for generating a main pipeline network from a districting problem was presented. In reality, the subdivision of an informal settlement area into individual districts and the introduction of infrastructure are strongly interrelated. By integrating criteria with implications for a piped water supply, potential routing options were identified during the derivation of the basic areas. At the same time, the basic areas allow social, cultural and ethnological factors as well as socio-spatial relationships to be adequately considered. Districting was based on the criteria of balance, compactness, contiguity and complete and unique assignment. The procedure was used in this paper to generate a superordinate main pipeline network. From this, further subdivisions can be performed by the same algorithm. In this way, a gradual upgrade of the entire informal area is achieved. While the first stage enables the provision of basic services along the district boundaries, the distances for the population can be successively reduced in later stages by branching off supply lines from the main pipelines into the settlement area, as in the approach of Mosbach et al. [44]. The honeycomb layout of the main pipelines also ensures maximum flexibility for further upgrading measures. The intake points into the respective upgrading areas can be selected based on the prevailing development pattern along the main pipelines. This is very important, since forecasts about the continuous structural changes in an upgrading area are virtually impossible. The geometric approach of the recursive partitioning algorithm used allows for easy transfer to other areas and is extensible due to its modular design. However, the lack of a general evaluation measure and the subjectivity of compactness leads to the fact that the results must also be visually estimated despite automated area partitioning. If necessary, the tight coupling of the method to QGIS allows for quick individual adjustments, enabling the consideration of additional, user-specific criteria. In this case study, 3% of the basic areas were subsequently adjusted manually, thus indicating a high degree of automation.

To further reduce manual interventions, a second phase of districting can be implemented. Based on a contiguity graph representing the neighborhood relations of all basic areas, it can be determined whether the district membership of a specific basic area can be further optimized. In the case where a specific basic area is surrounded by the majority of basic areas of another district, the district membership can be determined using a boundary-length weighted function if a new assignment of that basic area should be sought. The underlying admissibility and balance criteria of recursive partitioning should be considered.

Despite the good results, the method does not guarantee that the introduction of a water supply structure is even possible in the generated districts. Theoretically, areas that do not have room for the introduction of a piped water supply structure as a result of high compactness combined with high building density can be formed. In these cases, subsequent pipelines can only run along district boundaries. However, this is a problem independent of the method and cannot be addressed without relocation measures. One solution could be an interaction of the method with the reblocking approach of Brelsford et al. [17].

Further studies should be carried out on the development districting. For example, an interaction of clustering methods and districting could also be target-oriented with regard to the introduction of a line-based infrastructure. An extension of the recursive partitioning algorithm should also be worked on, so that the simultaneous consideration of several balance measures as well as of a global compactness becomes possible.

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