GIS BASED PLANNING OF INFRASTRUCTURE IN NEW TOWNS THE CASE OF NEW FAYOUM

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ABSTRACT:

The planning and engineering of an infrastructure system is an iterative process whereby the engineer tries to achieve an optimal solution within the applicable engineering design criteria. An optimal solution will generally have a number of characteristics, for example in terms of costs: the solution chosen should lead to favourable construction costs and low maintenance costs. On the other hand, the design should be such that all inhabitants have access to a service, that this service is of good quality and that the organization responsible is able to take care of the infrastructure once constructed. In a design process, these aspects are explicitly and implicitly present, however often not addressed in a systematic manner. In the current study, the use of GIS in infrastructure planning will be explored as a means to provide such systematic approach. The study addresses the application of GIS in the planning and design of urban infrastructure in a newly planned urban development in Egypt called "New Fayoum", focusing on the planning and design of a new sewerage network with pumping station facilities and a road network. It is concluded that GIS can be an important tool for the success of the Egyptian Government new urban development strategy to facilitate informed decision-making in its planning process if it incorporates GIS in the planning system.

1. INTRODUCTION

1.1 The Need for a New City in the Old Fayoum Governorate

The Old Fayoum governorate is located in the western desert 90 km to the South-west of Cairo the capital city of Egypt. It has a total area of 6068 km^2 and a population of 2.098.250 (1999 census) with a 101% expected increase in the year 2020. The governorate is basically an oasis, surrounded by desert in all directions except for the South-east direction where it connects to the Bani Suef governorate. The governorate consists of 5 main cities (at the same time administrative centres) namely Fayoum (the capital of the governorate), Ebshway, Etssa, Tamayah, and Sonoros that in its turn consists of 44 local units, 159 villages, and 1620 farms with a total of 1748 urban and rural communities. The following satellite image shows the location of the Old Fayoum governorate in relation to the Egyptian Delta, while the subsequent map shows the Fayoum governorate with its administrative units.

With the high population growth of the Old Fayoum governorate and the high demand for housing, the Government has started the planning and development of a new area, "New Fayoum", an area of approximately 1300 Fed or 546 ha to be located in the Fayoum Governorate at a distance of 12 km from Old Fayoum. The new city is planned to take population from old Fayoum, and to create economic conditions in an appropriate living environment, while at the same time solving some of the environmental problems of Old Fayoum.

1.2 Process and Main Criteria for Location Selection

In order to understand the context for the study, some information is provided on the process of location choice for New Fayoum. The organization of Urban Researches and Studies under the Ministry of Housing, Utilities, and Urban Communities in Egypt has as its mandate the identification of suitable sites for urban development. The organization follows a procedure that uses criteria in the evaluation of potential sites. For the selection of the New Fayoum urban development a new site has been identified, based on the following criteria:

1. The location is on desert land, away from agricultural lands.
2. The location is close to the main road system.
3. The location is relatively near to Old Fayoum.
4. The location is close to water and electricity resources.
5. The location offers possibilities for further expansion in the future.
6. The land is available, which means that the Government owns it and no other development plans are considered for the same land.
7. The site has a suitable topography, which means that it is relatively flat and the change in elevation is rather gradual.

Before a final location was selected a further study into the environmental and natural conditions of the site was done; this study consisted of 6 main elements:

1. Identification of the main features of the new city location.
2. Climate.
3. Topography.
4. Geology.
5. Environmental pollution.
6. Environmental impact assessment.

A next step involved additional preliminary studies on the following aspects:

1. The expected public services needed for the new city according to the expected population.
2. The expected housing needed for the new city according to the expected population.
3. The General planning of the city including the limitations of the urban planning such as the topographic, demographic, economic, and environmental limitations, the main recommendations affecting the planning and the architecture design of the city, the main guidelines and decisions directing and leading the planning of the city, the urban land administration studies to fulfil the land requirements for different land uses in the target year, the planning alternatives possible for the city and the evaluation of each alternative, the general suggested plan for the city after the evaluation of the alternatives, the optical or visual formation of the new city, the prioritisation and the implementation stages.

Unfortunately all of the above mentioned studies are carried out using traditional procedures without any involvement of GIS analysis. For this reason, the paper explores whether GIS could be a suitable tool to assist in the location selection and impact studies.

2. SCOPE OF THE STUDY

For this area, which has a planned population of 100,000 people in the year 2017, detailed plans and engineering designs have been made for the various infrastructure facilities, including the road system, the sanitation, drainage and drinking water supply systems - including pumping stations and treatment plant - and the irrigation system for the green areas to be established.

The planning and engineering of an infrastructure system is an iterative process whereby the engineer tries to achieve an optimal solution within the applicable engineering design criteria. An optimal solution will generally have a number of characteristics, for example in terms of costs: the solution chosen should lead to favourable construction costs and low maintenance costs. On the other hand, the design should be such that all inhabitants have access to a service, that the service is of good quality and that the organization responsible is able to take care of the infrastructure once constructed. In a design process, these aspects are explicitly and implicitly present. In the current study the use of GIS in infrastructure planning will be explored. GIS can be a useful tool in the planning of infrastructure in newly developing areas. This will be demonstrated in this study by implementing some of the applications of GIS to the planning and design of a new sewerage network with pumping station facilities and a road network. In addition some cost estimates will be undertaken for sewerage, and roads. This GIS based work follows on from CAD based work that was carried out by the responsible organization GOPP in the preparation of spatial plans and engineering designs as an engineering drawing and spatial design tool. These CAD products form the basis of the spatial information used in the study. The preference of GIS over CAD stems from several reasons, as expressed by Goodchild, 2001: “CAD systems generally lack the ability to deal with a wide range of geographic data types, multiple attributes, relationships between features, and referencing to geographic coordinate systems, because their main application is in the design and drawing disciplines”. “GIS is inherently more attractive for infrastructure applications, because of its ability to integrate data from multiple sources, as well as for the three reasons already cited”. Using GIS we are therefore able to explore spatial phenomena and their relationships better than we would otherwise be able to.

3. OBJECTIVES

In this study we are looking at some aspects of infrastructure development in New Fayoum:
The Road system; To provide access to the inhabitants of the new area, an extensive road system will be constructed. The initial engineering design that has been made for the road system will be analysed. The design of the road system is basically defined by the Final Surface Level (FSL) in combination with the road width and the material of construction. In this study we are going to visualize the road system in the terrain to see how it is designed and how it fits with the natural conditions. We will check the maximum slopes and calculate the volumes of cut and fill and the corresponding costs.
Pumping stations; In the area, three pumping stations need to be constructed, to pump the water up from the lowest point of the sewer system to the sewerage treatment facility. The proposed sewer system delivers the sewage through a piped system under gravity to these three pumping stations. In this study we will investigate what are possible locations for the sewerage pumping stations by looking at the elevation characteristics of potential sites and at secondary characteristics such as the required area for construction, the slope and the landuse.

Sewerage systems; We are going to look at the design of the sewerage system in one of the zones. A layout of the sewerage system is proposed and we will evaluate whether this proposal is feasible in terms of its hydraulic performance, and in terms of engineering design requirements, particularly looking at pipe diameters, slopes and soil covers.

4. DATA MODELLING

4.1 Why Carry Out Data Modelling?

A data model is a representation of some real world phenomenon for which information will be stored in a database (Goodchild, 1998). Storing information in a database has many benefits such as allowing the user to perform complicated analytical functions and queries, handling large amounts of data, imposing certain rules on the stored data, concurrent use of the data by a number of users, and much easier data updating. In addition, storing the information in a database is the only way to perform any analysis in the GIS environment. In attempting to model the real world in GIS, we have to find an appropriate representation. This representation should have certain characteristics in common with the real world, particularly those characteristics that we are interested to study.

4.2 Data Models for the Main Processes

The main elements modelled in the study are the road network and the wastewater network including the sewers, the manholes and the pumping stations. Other elements were modelled also, such as the city land use zones, the land blocks and parcels. Of these, only the land use map was used in the analysis, the others were modelled for better presentation of the results of the analysis and for future use. The following table shows which real world element was modelled and what the corresponding representation in the GIS environment was.

Real world element	GIS representation
Road Network Section	Line
Road Network Intersection	Node
Sewers	Line
Manholes	Node
Pumping Station	Graphics polygon
Zones	Polygon
Blocks	Polygon
Parcels	Polygon

Table 1. The real world element with its corresponding GIS representation

5. ANALYSIS

5.1 Cut and Fill Computation for the Whole Road Network of the City

As indicated in earlier we can use the GIS to calculate the volumes of cut and fill and evaluate the corresponding costs. The calculation of cut and fill forms the backbone of the total road cost calculation. Other costs on pavement and construction are in principle a function of length of the road system and can be estimated without further analysis when the costs of cut and fill are known. The design of the road system is basically defined by the Final Surface Level (FSL) in combination with the road layout and the material and process of construction. In this section we will check the maximum slopes, calculate cut and fill and visualize the results. Given the total road network segments and nodes (final surface level) and the digital elevation model for the city (natural surface level), it is required to compute the volume and the depth of the cut and fill operations for the whole network. In the box below, the methodological steps that are undertaken to compute the Cut and fill volume and depth are explained.

1. Starting with the road network centreline layer, a field is added to the attribute table called the buffer width, to calculate for each individual segment the road extent. Note that the buffer width is equal to half the pavement width of the road.
2. The GIS is used to create a buffer around the centrelines of the roads, using the width calculated in step 1, for each individual road segment.
3. This road buffer layer is converted to a raster format.
4. The road raster buffer layer is incorporated into the Digital Elevation Model (DEM). This results in a raster layer for the planned road network with the corresponding elevations of the natural surface, (further referred to as NSL, Natural Surface Level).
5. The vector buffer layer gained in the 2nd step is used to build a polygon topology for this layer
6. A road network is usually designed as a collection of points in regular intervals, representing the spatial pattern of the road layout, the elevation and the slope between two adjacent points. Using the layer with nodes of the proposed road network (see figure 1) which has the proposed final surface levels after construction, we are able to calculate all elevation values in between the nodes, by a spatial interpolation in the raster environment. This procedure assigns an elevation value to all the cells located in the extent of the road network on the basis of a linear interpolation between the two closest nodes. This results in a raster map of the road with the final surface level (FSL). The final surface level will be used for the cut and fill calculations and to produce a slope map for the whole road network to determine its compatibility with the Egyptian code of practice for the design of urban roads.
7. With the NSL and FSL layers and using a raster calculator we subtract both layers to get a new layer that indicates the depth of cut or fill (figure 2)
8. With the same NSL and FSL layers and using we calculate the volume and the surface area of both cut and fill operations.

The map (figure 2) and the chart (figure 3) show the totals of the cut and fill volumes and the areas needed to construct the road network. The light blue colour in the map represents the areas that need to be filled and the light brown colour represents the areas that need to be cut. The red colour represents the areas unchanged, which means that no cut and fill operations are needed for those areas. It can be seen from the map and the pie chart that the volume of cut is slightly larger than the volume of fill which means that the soil resulting from the cutting operations can be used in the filling operations and only a small part has to be transferred outside the city or used in other purposes. It is also clear that most of the road network area falls under cut or fill operations; only a very small portion is unchanged, which means that the cost of the cut and fill operations will be high. On the basis of these results, easily cost estimates for cut and fill of the entire road project can be made.

The map in figure 2 shows the cut and fill needed to construct the road network of the city with the corresponding depth in gradual colour. The gradual blue shows the areas of fill starting from dark blue (10 meters depth of fill) to light blue (2 meters depth of fill). The gradual brown shows the areas of cut starting from dark brown (10 meters depth of cut) to light brown (2 meters depth of cut). It is clear from the map that only small areas of the road network need a deep cut and fill, most of the network falls under low and medium depth of cut and fill which makes the cut and fill operations easier. Taking a look into the final slope of the road network after construction, which can be generated from the final surface level of the road network, we will find that a limited number of slopes are violating the limitations of the vertical slopes in the Egyptian code for the design of road network. According to the code, the New Fayoum roads falls under the local and the secondary roads which permits a speed of 50 and 60 Km/hr and a maximum vertical slope of 9 and 12 % respectively. Some adoptions should be done to the design to restore the road network compatibility with the Egyptian code. It is also shown that the volumes of cut and fill are rather high, which will lead to high construction cost. On the basis of alternative designs more optimal solutions can be found and recalculated using a similar procedure.

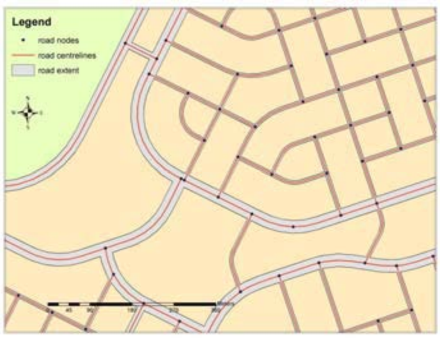

Figure 1. Section of the road network of new Fayoum: nodes, centrelines and variable *buffered road extent*

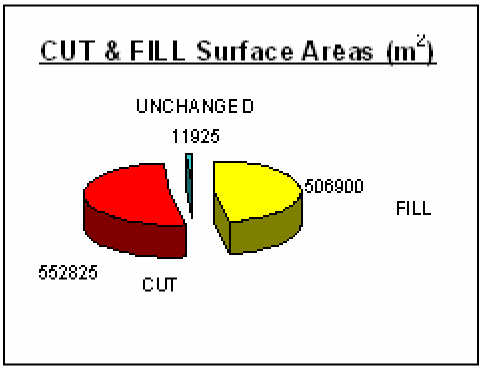

Figure 2. Cut and Fill

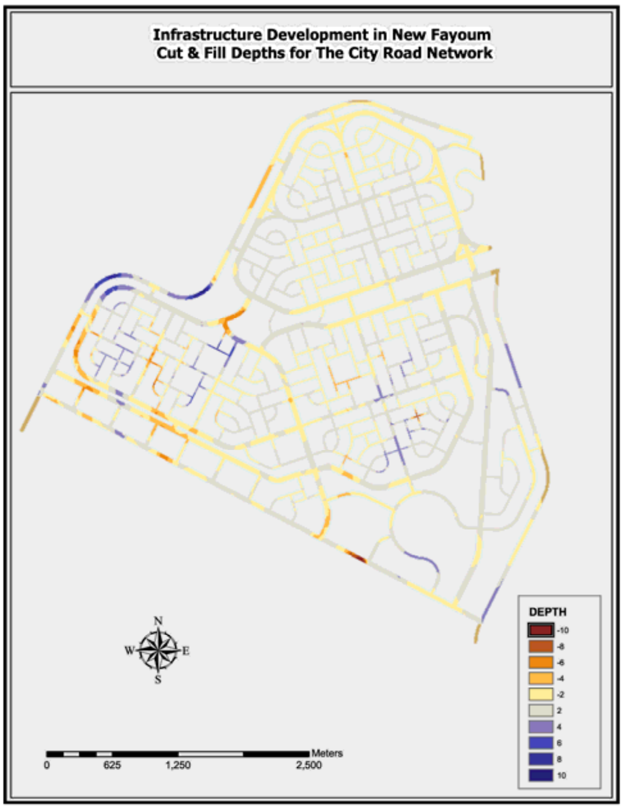

Figure 3. Map of the cut & fill depths for the city road network

5.2 Finding the Optimum Pumping Station Locations

As indicated earlier, for this area three pumping stations need to be constructed, one for each sewer system zone, to be able to pump the collected water from the lowest point of the system to the sewerage treatment facility. In this study we are defining the optimum locations for sewerage pumping stations by looking at the elevation characteristics of potential sites and at secondary characteristics such as the required area for construction, the slope and the landuse. In summary the criteria are:

1. A landuse type of either ‘recreational’ or ‘green area’.
2. An as low as possible elevation inside each zone.
3. A minimum area of 40*120 m (standard layout of pumping station facilities).
4. A relatively flat area (small slope values and little variation in slopes).

The following steps offer a brief explanation of the methodology undertaken to find the optimum location for the 3 pumping stations.

1. A zone layer was created for each sewer system zone using the available layer for the 3 zones.
2. This zone layer is rasterized to a raster format.
3. The vector zone layers gained from the first step are clipped with the land use layer to get a land use layer for each zone.
4. The 3-landuse layers are rasterized.
5. The landuse is reclassified into according to the criteria mentioned above.
6. The raster layers of the zones and the DEM of the whole city are combined to get a layer for each zone with the corresponding elevation.
7. According to the variation in elevation inside each zone the elevations are classified into two types SUITABLE (1), and UNSUITABLE (0). This is an iterative process. A good start approach is to take the elevation values of the lowest residential blocks in the zone that need to dewater to the pumping station. This can be easily done visually by overlaying the zones classified as residential on the DEM and determine which zone is located in the lowest area. Alternatively, the zone layer can be rasterised and the average elevation per residential block can be calculated. All land elevation values in the zone that are lower than the lowest residential block are possible locations. Now there are two possibilities: 1: The process does not result in an area that comprises with the criteria mentioned above, i.e. the area classified as suitable is too small to fit the pumping station. In that case the analysis needs to be enlarged by looking at the areas that are up to 1 m higher than the lowest building block. 2: The process results in a lot of locations and many possibilities. Repeat the exercise with a threshold value that is 1 m lower than the lowest elevation. Areas that are suitable are given a value 1 in the reclassification operation, areas considered unsuitable are given a value 0.
8. Then using both the reclassified raster layers for the landuse and the elevation inside each zone we use to add the 2 layers together to get the areas inside each zone with the suitable height and landuse at the same time (value=2).
9. The final stage is to draw a rectangle of (40*120) m and to place it interactively in one of the suitable areas inside each zone to define the ultimate optimum location. This is done visually on the basis of elevation information and area size and results in a final preferred location.

It can be seen from the map that a number of possible locations (shown in green) are suitable for the construction of the pumping stations according to the selection criteria especially in zones 1 and 2 where a variety of locations are considered suitable. The final selected locations (shown in yellow) were chosen visually by an interactive placing of the required area for the pumping stations in the red spots representing the suitable areas for the construction of the pumping stations.

Comparing the outcome of the GIS analysis with the actual traditional procedures for locating the pumping stations we can conclude the following:

1. The GIS analysis provides the user all the areas within the desired elevation limits and landuse type which gives the designer a variety of locations to construct the PS in case more than one location is suitable whereas when using the traditional way the designer might overlook some suitable locations.
2. One of the most important benefits of using the GIS analysis for locating the pumping stations is its ability to work with more than one layer. When using the traditional way the user still has to deal with each of the involved layers separately to find the suitable location. This is a hard thing to do especially when dealing with a large number of layers and conditions at the same time.
3. The GIS analysis is more capable of adapting to change in the selection criteria like the proposed landuse type or the elevation, the same process can be run again with a change in the values of the criteria or adding a new criterion. Whereas in the case of the traditional way the designer has to go through the whole process of selection again using the new selection criteria.
4. With the GIS analysis a better presentation can be made to show how the selection was made step by step which gives a better understanding of the whole process for the designer himself and for the decision maker.

Figure 4. Map of pumping station locations

5.3 Planning and Engineering Design for a Sewer Line

For the city sewer network a basic engineering design was made prior to the study by the authorities involved. This could also be done with the help of GIS, which would lead to large savings in design time. To demonstrate how this works for only one line, we are planning the location of a new line, a main collector. The engineering design is based on the Egyptian design code and practice, as explained in appendix 4, based on the application of the Manning formula for pipelines. Other, more advanced methods using hydrodynamic models could have also been applied, but the idea is here to stick to the applicable design process. As indicated in table (3) after we use the Arc Toolbox to convert the sewer network from the CAD representation to the GIS environment, we build the topology for the whole network as line (sewers) and nodes (manholes) to remove any errors and to ensure the connectivity of the network for any further network analysis to be done in the GIS environment. After this, we create a geodatabase for the sewerage system including the sewers and the manholes. The following steps demonstrate the planning and design of the new sewer line. The steps consists of three stages, each stage takes place in a different software environment.

Stage (1) ArcGIS stage:

1. The wastewater network layers (Manhole layer, Wastewater network, new line manhole layer, route of new line) are added. 2. A new line manhole layer is created and new manholes are added to the new line at a distance of approx. 50 m. and at crossroads. (x,y) coordinates are obtained for the manholes that have just been added using an advanced calculation with the VB script:
Dim dblX As Double Dim pPoint As Ipoint Set pPoint = [Shape] DblX = pPoint.X   Likewise for the Y coordinate

Stage (2): ILWIS software:

1. Importing the *new line manhole* layer. 2. Open the attribute table and add a new field of the final surface level "FSL" 3. Calculate the "FSL" value using the following condition
FSL = Mapvalue (dem, Coord(x,y)). This calculation extracts for each manhole location the corresponding elevation from the DEM
4. Export the table of the new line manhole layer to a database table "dbf" 5. Save and close ILWIS.

Stage (3): MS Excel stage:

1. Open the table that you just exported from ILWIS and add the following new columns:
• Diameter = 300mm. • Slope = (1/ Diameter). • Distance between manholes = SQRT [(x2-x1) 2+(y2-y1) 2]. • Top limit = FSL – 1.2m. • Top Cover = FSL – 1.2 for the first cell. • Previous cell - (distance*slope) for the rest of the cells • Invert Level = Top cover – (Diameter/1000). • Cover depth = FSL – Top cover • Invert depth = FSL – Invert level.
2. Draw an excel graph between FSL, Invert level and check the minimum cover of 1.2m. 3. Change the slope to fit the cover.

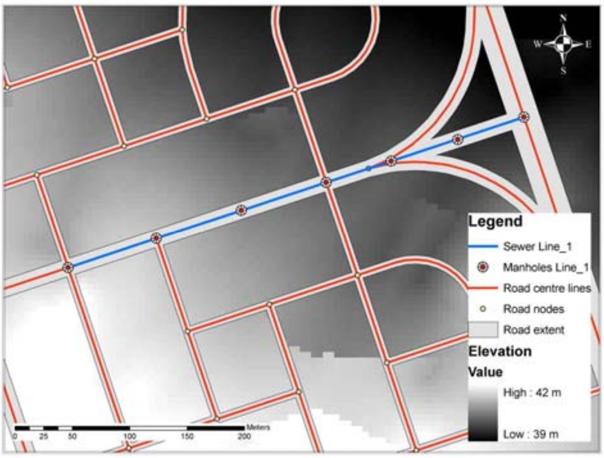

Figure 5. The layout of the proposed new sewer line with Manhole locations

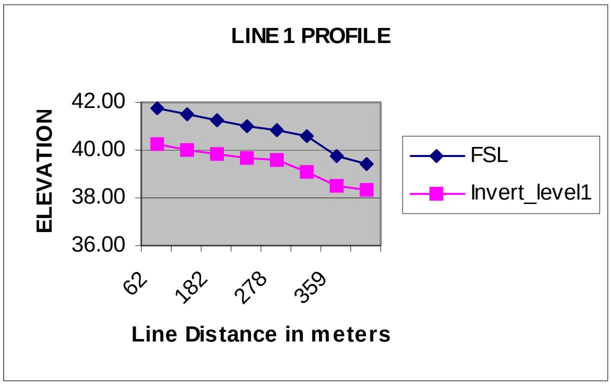

Figure 6. The final surface level and the invert level for the planned sewer line

As shown from Figure 6 the final surface level of the sewer line and also the invert level are shown. The designer can interactively in the Excel environment change the slope or the diameter of the sewer to fulfil the minimum cover of 1.2 m over the sewer.

6. CONCLUSION

In this paper we have addressed some aspects of the design of urban infrastructure with the use of GIS. GIS has proven useful in aiding the technical design of the road network through a buffering operation using design road widths. Doing so has enabled the automatic creation of the road network extent and layout. In combination with a DEM, easily cut and fill calculations can be made. The DEM is also used in evaluating pumping station location and designing a new sewer line. The basic advantage of using GIS in these kinds of design calculations is in its ability to combine different layers of information and its easiness and speed in calculating and visualising important design aspects based on geographical information. Calculations that would take weeks to complete by conventional methods can now be finalised in a matter of days. Although only a limited number of analysis were made and many more are possible, we can conclude that GIS can be an important tool for the success of the Egyptian Government new urban development strategy to facilitate informed decision-making in its planning process. It can play a role in both main objectives of the Government strategy: to improve the existing urban structure by improving existing housing and infrastructure and in developing desert areas by establishing new cities. In the latter case the chances are significant as the development of the GIS system can be incorporated in the planning system. When new networks and infrastructure are being provided in developing cities it is relatively easy to start from scratch with a GIS. Doing so offers the advantage that the digitisation of networks and the setting up of attribute databases can quite smoothly be dealt with during the engineering stage, as these data need to be generated anyway and this offers sufficient benefits already in terms of engineering design (Brussel, 2001). Following an approach which includes a role for GIS analysis in establishing new cities, will potentially save a lot of money and effort for the Egyptian Government, especially in the long run. In the future more planning challenges will occur resulting from the expected growth of these cities. Using the GIS as a tool from the start in locating, planning, and management of infrastructure in these new cities can guide the developmental process and help prevent and overcome future difficulties.

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