Incorporation of Water Distribution Network Costs in Water Supply System Design Highlighting the Strength of Raster GIS Modelling

D.M.S.S. Dissanayake and N.T.S. Wijesekera

ABSTRACT

Design of Water Supply Scheme is very complex and challenging with the numerous options for source, Towers and Network Layout. It demands a several map based analysis to determine suitable layout with intake locations and intermittent storages. Spatial modelling in GIS using a raster format enables a water supply engineer to incorporate the spatial variability, parameter uncertainty, changes to decision objectives, exploring the conceptualizations, and time saving while providing the facility to not only visually explore the result but also to quantify in a meaningful manner. Raster model was developed to demonstrate the strength of GIS and to analyze tower locations and water distribution network layout options in Hanwella DSD area, Sri Lanka. Demonstrating a simple method to incorporate tertiary level pipe networking costs, this case study demonstrates the evaluation of the least cost distribution network for the two alternative tower locations that would produce the same revenue.
To demonstrate raster GIS potential in the Water Supply and Drainage sector through a case study application of cost based tower location selection combining the impact of terrain features and consumer settlement distribution.
In the present study, three options were considered in order to supply water to the project area with proposed two source points. After obtaining lease cost paths to lay distribution network under each options considered, path costs were compared in order to identify best alternative.
There is a 36% Variation of cost between options and Out of three options, third option with the lowest cost will not be an effective option since even though both source points were used, source 1 will be used supply only for two destination points. Both have capability to supply water effectively and economically to particular area. But supplying water with S2 tower will be the best option with 33% less cost compared to highest cost option and only 2% higher than least option.

KEYWORDS: Water Distribution Network, Pipe laying Cost, Raster GIS, Spatial variations, National Water Supply &Drainage Board

1. Introduction

Demanding occupations pushing for time savings and improving life styles aiming for more and more comforts call for reliable and affordable services at the doorstep of almost every human. In a long list of desires, the demand for safe pipe borne drinking water is in the forefront. Most do not have the luxury of easy access to their own surface of groundwater suitable for consumption. Increase of population in one hand demand for more and more water and their needs on the other hand pollute the available limited quantities. All over the world, urban units are generally well looked after with pipe borne water. The present demand is in the rural areas which have greater spatial extents, scattered dwellings, greater surface undulations, larger distances to sources and storage. In Sri Lanka most new water supply projects are in semi urban or rural areas. Hence the planning of Water Supply Schemes is a very complex and a challenging task because of the numerous options available for sources, towers and network layouts. It demands decision making based on many geographic features that are interlinked with many subjective parameters. Geographic features fall in to a many categories represented by either points, lines polygons or surfaces. The subjective parameters also depend on many physical, social and political factors. Therefore water supply scheme design requires a several map layer based complex but flexible analysis to determine a suitable layout with intake locations and intermittent storages. Rural communities are the neediest among those who require pipe borne water supply. Therefore, it is important to investigate and study in this context. Recent GIS technology enables spatial modelling which is a proven tool for many resource and infrastructure planning works. Though there are applications carried out elsewhere in the world (Sitzenfrei, Möderl, & Rauch, 2013), case study applications and guidance material for Drinking

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Water Supply Systems in a Sri Lankan context is a gap that needs filling. In case of GIS, though Vector formats provide ease of conceptualization, Raster format is the versatile tool for complex data packed real life case study applications. Spatial modelling in GIS using raster format enables a water supply engineer to incorporate the spatial variability, parameter uncertainty, changes to decision objectives, exploring the conceptualizations, and time saving. Unless raster applications are carefully executed it's advantage in easy computing is lost due to difficulty in visualizing.

Accordingly the present work undertook the task of demonstrating the planning potential of GIS in the Water Supply and Drainage sector through a case study application of cost based tower location selection combining the impact of terrain features and consumer settlement distribution.

The National Water Supply and Drainage Board, with a preliminary analysis had identified two locations to erect a water tower at Hanwella DSD in the Western province of Sri Lanka consisting 42 GNDs spread over nearly 64 km2. The planning requirement is to identify the best distribution network by considering factors such as, pipe laying expenditure associated with costs of road and stream crossings, safety of road user community, variation of excavation and backfilling costs.

2. Objective

Aim of this study is to demonstrate the planning potential of GIS in the Water Supply and Drainage sector through a case study application of cost based tower location selection combining the impact of terrain features and consumer settlement distribution.

3. Materials and Methods

3.1. Objective Function

To identify an economical solution it is necessary to consider cost of network establishment since the problem reduces to selecting an alternative with the least cost distribution network. Since, water distribution is done only by the NWSDB, the water tariffs would depend only on the consumption. Since the total revenue generated will depend only on the location of tower, the cost of laying the network becomes the selection criteria.

Spatial distribution of water demand, road type , and terrain along which the network has to be laid, Culverts or stream crossings in the pipe route and Land use variability are the main parameters affecting pipe laying costs. According to the demand, pipe diameters, types, fittings and other accessories vary. Road Development Authority charges for road repair and maintenance vary based on the road type which needs excavating. Terrain variations demand extra effort, tools, material and skills. Special care and design is needed to lay pipes across streams or rivers requiring more time, machinery, detour paths etc. Excavation costs do vary with land use.

Consideration of these factors require careful establishment of the objective function and then its mathematical representation. The objective function used for the present work is in equation 1. The other parameters were assumed as a non-significant.

Cost of Pipe laying = function (Demand, Road type, Slope, Culvert crossings, Land use) --------(1)

In the absence of a proven mathematical relationship between the parameters, the present work conceptualized that, the total effect on the objective would be the cumulative influence of the selected parameters. Accordingly, the mathematical representation was taken as in Equation 2.

$$P = D + Rt + S + Cu + L \quad \text{---------------------} \quad (2)$$

Where P is the Cost of Pipe laying, D is the demand for water, Rt is the road type, S is terrain variation, Cu is culvert crossings and L is the land use.

Table 1. Objective function in systems concept

		Objective	Parameters
1		Cost of pipe laying	Terrain(1a), Road(1b), Culvert(1c), Land use(1d), Demand(1e)
1a		Terrain	Elevation, Slope
1b		Roads	Road type, Land use
1c		Culvert	Watershed area, Rainfall
1d		Demand	Population

When it comes to systems concept, cost of the terrain is again a function of cost of elevation and slope. Hence, that has been considered when assign values and weights. Cost of roads may vary with the type and land use of relative area. Based on amount of rainfall and watershed area, cost of culvert crossings may vary. Similarly, according to the population cost related to demand may vary. Therefore assigning values and weights for creating cost surface have been carefully done by given due respect to these relationships. Further, it is assumed that cost of each main parameter linearly proportionate to the cost of above discussed sub parameters. Quantification (Valuation) of each parameter has been carried out based on general notion and using judgmental decision-making.

3.2. Base Layers

Point, Polyline and Polygon data and Raster images are used with their attributes to create required map layers. Existing Road Network GIS vector map (1:50,000) was available as a polyline shape file with type and length available as attributes. Land use vector GIS map of the area was digitized from 1:50,000 topo maps as a polygon shape file having 9 land use categories attributes. Contour map of the study area available was a polyline shape file vector version and attributes of elevation. Stream network, was also digitized using 1:50000 topo sheets. Details of GIS data are in Table 2.

Table 2. Spatial data and data types

Data	Type	Resolution	Units of measurement	Attributes
Road network	Poly line	1:50000	Meters	Type, length
Contour map	Poly Line	1:50000	Meters	Elevation
Landuse	Polygon	1:50000	Square meters	Area, Type
Stream network	Poly Line	1:50000	Meters	Length
Population	Polygon	GND	Number	population
Rainfall Gauging stations	Point	Monthly	Millimeters	Rainfall

3.3. Analysis

Vector road network map was converted to a raster layer and then reclassified to 4 classes of roads and values were assigned to the type. Raster resolution of 5m was adopted for this whole study. Land use map which was polygon layer converted to raster and reclassified in to six main classes based on type of land use.

Table 3. Road Classification

Road Type	Value	Justification
A	7	RDA charge high & excavation hard
AB	5	RDA charge less than A class roads
B	2	Low charge by RDA and excavation relatively
Other	1	Less or no charge and excavation easy

Table 4. Land use classification

Land use	Value
Rubber	3
Paddy	4
Coconut	5
Homestead	7
Marsh	8
Stream	9

Triangulated Irregular Network (TIN) was developed using 5m Contours and Spot Heights and then the TIN model was converted to the Digital Elevation Model (DEM). The slope raster was created from the DEM and then reclassified in to 3 classes.

Table 5. Slope Classification

Slope %	Value	Justification
< 2%	1	Mild slope less complicated construction.
2% - 7%	5	Relatively complicated construction
> 7%	9	Very complicated

Watersheds were generated for each culvert locations using watershed tool. Peak flow for each culvert point was estimated based on catchment area since rainfall variation is negligible over the project area. Runoff coefficient assumed to be similar over the catchment. When assigning values, Higher value is given for higher peak flows.
Stream network was generated using the DEM which was burned with the physical streams. Flow direction computation, filling of sinks, flow accumulation etc., were carried out using the flow direction, fill and watershed tools.
A comparison of stream network generated with the threshold flow accumulation value of 3000 was selected after matching with the existing physical streams. Raster to Vector conversion tool was used to create the stream network polylines. Stream and road network enabled the identification of Culvert locations. Watersheds at each culvert location were generated with the use of watershed tool.
Vector map of GND polygons with population as attributes was converted to raster and reclassified as given in Table 3.

Table 6. Demand Classification

Population Type	Value	Justification
>2000	9	High demand
2000 - 800	5	Medium
< 800	1	Less demand

Then the cost surface raster was created by overlaying the all five raster layers reclassified as in Table 3 to 6 using Raster Calculator tool.

Three options were considered in order to supply water to the project area with proposed two source points. First option was to supply water to all area with source point 1. Provide water using source point 2 was second option while supply water to the project area using both source points was considered as third option. Cost distance raster for the three options were created using cost surface as the input cost raster and service reservoir points as the source points. While creating the cost distance raster cost backlink raster was also created as a requirement to create the cost path in the next step. Cost Path for the three options was created using

cost distance, cost backlink as input Raster and GND centroids as the destination points. Centroids of each GND were obtained by mean of point shape file using 'feature to point' tool.
Cost Path for the three options was created using cost distance, cost backlink as input rasters.

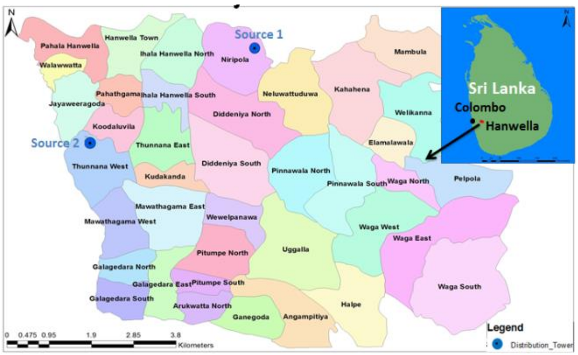

Figure 4 Project Area map

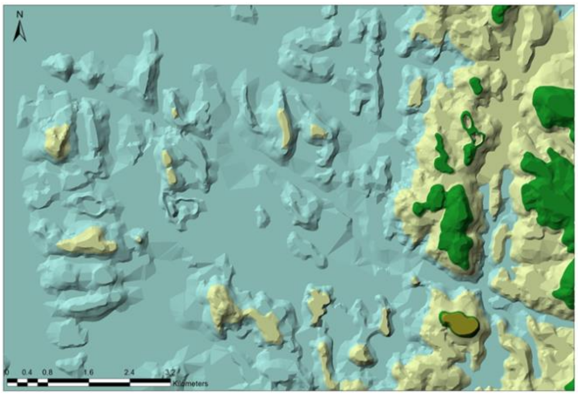

Figure 2 Triangulated Irregular Network (TIN)

Generated cost maps indicated that higher cost should be born to supply water to Eastern part of the project area. It is higher with the source point 1 and lesser with option 2.

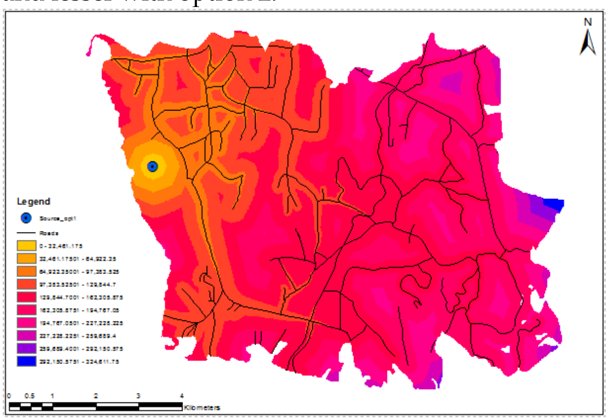

Figure 3 Cost distance map for option 1

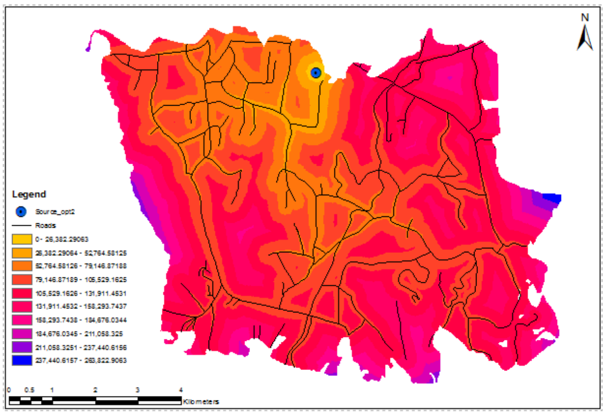

Figure 4 Cost distance map for option 2

There is a 36% Variation of cost between options and Out of three options, third option with the lowest cost will not be an effective option since even though both source points were used, source 1 will be used supply only for two destination points.
Both have capability to supply water effectively and economically to particular area. But supplying water with S2 tower will be the best option with 33% less cost compared to highest cost option and only 2% higher than least option.

Table 7. Path cost for each option

Option	Path Cost
Option 1	5,211,315
Option 2	3,905,357
Option 3	3,832,779

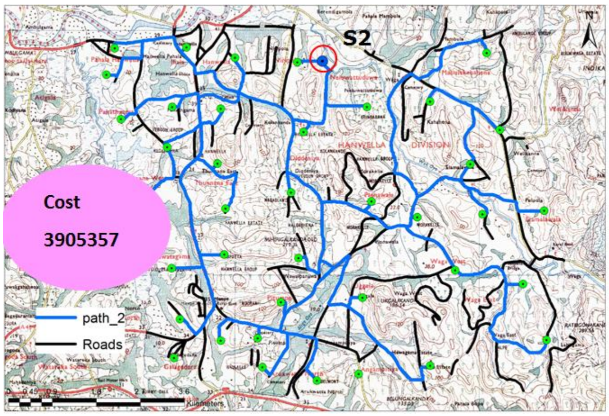

Figure 5 Least Cost path for Option 2

4. Discussion

Since design of water distribution network (WDN) is a very complex procedure, it is vital to know how each parameter varied in space. Using raster GIS modeling it was able to demonstrate that how each affected parameters towards WDN are varied over the project area. Conversion of parameter vector map layers to raster format enables obtain continues variation surface for each parameter. Apart from the land use pattern, road type and terrain, it was very much useful in incorporating rainfall variation and peak flow calculations in culvert and bridge crossing design. That shows how easily those complex scenarios incorporated in to process with GIS modeling.

In this present study, it was assumed that WDN pipe laying cost depends on only considered parameters. Apart from that it was assumed that no significant variation of considered parameters within 5m intervals. Therefore, 5m resolution was used in GIS modeling. Even coarser resolution like 10m or 20m may do not harm much to the result since this study shows variation is not much in finer resolutions.

This study was able to give comparatively good results since it shows significant improvements to traditional judgmental designs. Comparison indicated that better output generated through GIS modeling.

In case of further improvement to this study. It is proposed to consider incorporate zonal demarcation and valve location determination of the distribution network. If reliable data used for terrain and other such parameters it will be very much effective in doing so.

5. Conclusions and Recommendations

GIS analysis can be effectively used in the design process of water supply network apart from the monitoring and management tool.

Pipe laying Cost incorporation is successfully demonstrated and reliable data and furthers improvements to objective function may lead to better estimations.

The main issue and constraint was lack of data availability since approximations and assumptions had to be incorporated in computations in order to arrive to objective of the study.

If the reliable data is available, GIS can be used to identify valve locations and zone demarcations. It will be more effective designing water supply schemes for rural areas.

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7. References

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