Evaluation of Hydraulic Performance of Water Distribution System for Sustainable Management

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Abstract
Understanding hydraulic performance of water distribution system is crucial for sustainable management of a water supply system. In this paper, a case study of hydraulic performance was evaluated using WaterGEMS hydraulic model integrated with GIS at Tulu Bolo town. The WaterGEMS hydraulic model was calibrated ($R^2=0.93$) using measured data at 10 randomly selected nodes. Results of the analysis show that 92.6% of nodes reached optimized pressure ranging between 15m to 70m and about 1.27% are under permissible pressure while the remaining nodes have above the permissible pressure. The velocity of water in the pipes of the distribution system were found to be within the standard range from 0.2 to 2m/s which covers 82.7% (162 out of 196 pipes). Hence, the implementation of the WaterGEMs hydraulic model integrated approach with GIS enabled to estimate the pressure and velocity of the system with better accuracy and this will be helpful for sustainable management of the water distribution system.

Keywords Hydraulic performance · WaterGEMS · GIS · Sustainable water supply · Optimization

1 Introduction

Water distribution networks are set of geospatially interconnected hydraulic components transporting water for meeting demands of dwellers in a town or village. To effectively model these interconnected hydraulic components, the geospatial location and the ways of their interconnection both physically and functionally must be identified (Do et al. 2017; Herrin and Smith 2017). WaterGEMS hydraulic model integrated with GIS offers analytical solutions for modelling, designing and operational intelligence of water utilities. One of the major challenges in poor countries is that the water distribution network

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is inefficient and methods of collecting geospatial database of the network and its management is not up to the standard. Sustainable management of a water distribution system is crucial for optimal utilization of the system resource. Hence, to solve these problems, the distribution network was drawn by using GIS and Google Earth starting with partially plotted AutoCAD drawing of network elements. The plotting of pipes and other elements were imported and the missing information were completed in ArcMap.

WaterGEMS hydraulic model has a set of comprehensive modelling, management, and spatial decision support system for water supply network. Hence, this capability has been exploited which facilitates the realistic modeling of geometric networks as well as manage hydraulic network model data (Sudheer et al. 2019). Sudheer et al. (2019) reported that the ever-increasing demand can be fulfilled by designing efficient water distribution networks based on advanced computing systems including modern hydraulic modeling and designing softwares.

Shamsi (2004) described three basic methods of developing GIS based modeling application, i.e., interchange, interface and integration as a tool to diagnose the system water productivity and reduce cost. The integration of GIS with the hydraulic model WaterGEMS provides opportunities for spatial analysis, a system of record assets, and data management. The GIS integrated method was evaluated for the hydraulic performance of the water network and the results show the method is suitable (Alrayess and Ulke 2017; Eljamassi and Abeaid 2013).

Vairavamoorthy et al. (2004) investigated GIS integration with EPANET hydraulic model and applied it to a spatial decision support system for solving pipe risk mitigation problems of water distribution system. The contaminant entrance potential and potential pollution area of water pipes were displayed as thematic map in GIS and the areas resulting in high risk were identified from the GIS maps. Pindiga and Sani (2015) examined the GIS for mapping water distribution network and the task of GIS is locating underground pipes and the features installed within water supply. The logical architecture is studied by having the logical position of various features within the water distribution network which helps for the proper management, strategic planning and operation managements.

Kruszynski and Dawidowicz (2020) examined an integrated GIS and the hydraulic model to improve water supply and sanitary networks into one coherent management system, owing to which a holistic assessment of the functioning of the water and sewerage management system in the city is possible. Their work evaluated that the integrated system enabled them to regulate the hydraulic situation of the network to its optimal value at serviceable range and reduce age of water to the required level at the required spatial accuracy.

Water distribution system calibration methods are commonly used to obtain the values of roughness in pipes and real flow rate at nodes, which are considered input parameters in network analysis, by comparing pressure at nodes and flow along pipes obtained by the model with field data (Morosini et al. 2018). Calibration of pipe network models consists of determining the physical and operational characteristics of an existing system (Kapelan et al. 2007). Sampling techniques are studied by different authors (Kapelan et al. 2005; Bush and Uber 1998; Morosini et al. 2014). Accordingly, representative sampling points were taken among the junction node points so that the calibration is effective.

The poor spatial information of water distribution system features in the study area were addressed by GIS integration analysis. The developed spatial information can be utilized for future sustainable management of the water distribution network. Therefore, in this study, GIS integrated with WaterGEMS hydraulic model was used for analysis of the geospatial water distribution network of Tulu Bolo town.
2 Materials and Methods

2.1 Study Area

The case study was conducted in Tulu Bolo town, located at a distance of 80 km along the Addis Ababa to Jimma road. Tulu Bolo town is geographically located at 8° 38’ 30"N to 8° 40’ 0"N latitude and 38°12 30"E to 38°14 0"E longitude (Fig. 1). It has an average elevation of 2193 meters above mean sea level. It has 1058mm average annual rainfall and 18 °C average daily temperature.

2.2 Data Collection

Primary data were collected through direct measurement of node pressure at randomly selected nodes. Secondary data including: pipe material, pipe length, starting node, stopping node and pipe roughness coefficients, population data, layout map, cadastral, and pipe network distribution were collected from the town municipality. These are the input data required for modeling water distribution network. Among the collected data, the range of diameters of the pipes vary from 50 to 300mm, the total length of the water distribution network is 20.01km. According to Tulu Bolo town water supply office, DCI and PVC pipes were laid in in the water distribution network and the pipe ages are 17 and 11 years respectively. Their roughness coefficients are 130 and 140 respectively. The tank characteristics are Tank diameter is equal to 11.5m, Tank height: 5m, Base Elevation: 2227m, minimum
Elevation: 2227.6m, Initial Elevation: 2228m and Maximum Elevation: 2233m. The base demand including non-domestic demand was projected from the population of Tulu Bolo town for a design period of 20 years.

2.3 Modelling Process

2.3.1 Conservation of Mass

The principle of conservation of mass dictates that the fluid mass entering any pipe will be equal to the mass leaving the pipe since fluid is typically neither created nor destroyed in hydraulic systems:

\[ \sum_{\text{pipes}} Q_i - U = 0 \]  \hspace{1cm} (1)

where \( Q_i \) = inflow to node in the pipe (m³/s)

\( U \) = water used at node (m³/s)

At any node in a water supply system, the total mass inflows must equal the outflows plus the change in storage, in case of using storage tank.

\[ \sum Q_{\text{in}} \Delta t = \sum Q_{\text{out}} \Delta t + \Delta V_s \]  \hspace{1cm} (2)

where: \( Q_{\text{in}} \) = Total flow into the node (m³/s)

\( Q_{\text{out}} \) = Total demand at the node (m³/s)

\( \Delta V_s \) = Change in storage volume (m³/s)

\( \Delta t \) = Change in time (s)

2.3.2 Conservation of Energy

The total energy at any section in the pipe consists of three types of energy. There may also be head added to the system by pump or head removed from the system due to friction and any sudden change in the water flow system, the equation is written in terms of head as follows at any two Sects. 1 and 2 in a pipe:

\[ \frac{P_1}{\gamma} + Z_1 + \frac{v_1^2}{2g} + h_p = \frac{P_2}{\gamma} + Z_2 + \frac{v_2^2}{2g} + h_L \]  \hspace{1cm} (3)

where \( P \) = pressure (N/m²)

\( \gamma \) = specific weight (N/m³)

\( Z \) = elevation at a datum (m)

\( V \) = velocity (m/s)

\( g \) = gravitational acceleration constant (m/s²)

\( h_p \) = head gain from a pump (m)

\( h_L \) = combined head loss (m)

The headlosses in the pipes were estimated for this study using the Hazen Williams equation:
The Eqs. from (1) to (4) were used as the basic equations applied in WaterGEMS hydraulic model for modelling the water distribution network of Tulu Bolo Town.

### 2.4 Building water Distribution Network Geodatabase

The flow chart (Fig. 2) shows the hydraulic modelling process adopted in this study to find the optimal solution using WaterGEMS hydraulic model integrated with GIS.

The geodatabase for the study was created by applying the model builder to connect the hydraulic model with geodatabase in WaterGEMS for ArcMap. The hydraulic model

\[
h_L = 10.7 \left( \frac{Q}{C} \right)^{1.852} \frac{lp}{d^{4.87}}
\]  

where \( h_L \) = head loss due to friction

- **Q** = flow rate
- **C** = Hazen-Williams roughness coefficient
- **d** = inside diameter of pipe
- **lp** = length of pipe

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\]
was created by importing the water distribution network and the attribute data from the master geodatabase, which was created in ArcCatalog. All data points such as junctions, tanks, and end caps were imported as nodes and distribution network as lines. The hydraulic model components imported were used to directly manage entities through their associated GIS geometry by searching and accessing their attribute and simulation results.

### 2.5 Sample Size and Sampling Techniques

Water distribution network sampling techniques for model calibration followed the standard methods of water distribution sampling techniques (USEPA 2005). Therefore, representative, accessible, and operational samples were taken both at higher and lower pressure zones for sampling points. The location of nodes and pipes that formed the sampling frame for the calibration test locations were done by systematic random sampling. Therefore, as per the stipulated criteria for a low to highly detailed network model, 6% of all the junctions were taken as sampling points. Accordingly, 10 representative (6%) junction nodes were selected as sampling points. The location of the sampling site points are presented in Fig. 3.

![Fig. 3 Sampling points for measuring pressure data](image)
2.6 Population Projection

Among the different approaches of population forecasting methods, the study analyzed the method which performed well in terms of similarity and/or least deviation from the census population. The results of all the projections plotted against latest census population, and analyzed the approach which performed well in terms of similarity and least deviation from the census population were selected. Accordingly, the geometric increase method was adopted for further water demand calculations since it performed better population estimation in terms of similarity to or least deviation from the census population (Fig. 4).

2.7 Water Demand Assessment

Water demand estimation was made according to MoWR (2006) demand categories present in the study area (Table 1). Hence, for the design period of 20 years, the population of Tulu Bolo town will be 59,720 which is categorized under category -3. Based on this category of the town, the mode and levels of services for domestic demand estimation were utilized. Non

| Table 1 Estimated water demand up to 2040 |
|------------------------------------------|
| Population in 2019          | Projected number of populations | 2020 | 2025 | 2030 | 2035 | 2040 |
| 24178                       | Maximum daily demand             | 1219.82 | 1250.67 | 2628.79 | 3367.83 | 4253.72 |
|                            | Peak hour demand                 | 1829.73 | 1876.03 | 3943.19 | 5051.75 | 6380.58 |
domestic water demand was estimated as percentage of domestic water demand according to MoWR (2006). The water demand is the summation of all consumptions present in the study area and it determines the capacity needed from the source.

### 2.8 Spatial Demand Allocation

Demand allocation is the task performed in a water distribution network modeling for assigning the water demand of the study area. Allocation of calculated base demands to the nodes in the water distribution network through GIS integrated WaterGEMS hydraulic model is consisting of several methods. Three of the methods used in assigning demands were point load data, area load data, and Land use data. The point load data needs detailed household survey inorder to find the exact number of georeferenced billing meters data, nearest node and pipe within a service polygon. In area load data method, the corresponding area influenced by the node within the given network is estimated from the population density. From the methods of assigning demands by area load data, the method through proportional distribution by population practically applicable to most of the study areas where the demands to the nodes in the network are assigned by creating Thiessen polygons to the corresponding nodes. The last method in assigning demands through land use data methods, the demands are calculated by land use and population, and assigned to nodes in the network based on landuse classification. The methods of point load data and land use data methods were not selected in this study due to unavailability of georeferenced billing meter data, nearest node and pipe, land use classification in the study area.

The methods of assigning demands obtained through Theison polygon approach was adopted for calculation of nodal demands through proportional population distribution (Sudheere et al. 2019). The demand influence Theison polygon shapefile was created from the junctions and the point file containing the consumption data were set as a target vector layer and join vector layer respectively. The geometric ground was set to include all points that are contained within the polygon areas of the voronoi layer and the attribute field must be set. The GIS integrated with a WaterGEMS hydraulic model approach allocated consumptions of all the uses to the network node by proportional distribution of population. Demand polygon is constructed around each node of the pipe network of the distribution system of the town as shown in Fig. 5 with load builder facility.

### 2.9 Calibration

Calibration was performed with a help of Darwin calibrator feature of WaterGEMS using the measured pressure data from the randomly selected 10 sampling points. These measured pressure values were used to calibrate the parameters of the water distribution network mainly the maximum and minimum demands as well as the roughness coefficient of the pipes in the WaterGEMS hydraulic model. The maximum and minimum demand values at the nodes and the roughness coefficient were calibrated until they are fitting to the measured data at the selected nodes. Accordingly, adjusted demand values and roughness coefficient values were obtained from the calibration. The coefficient of determination $R^2$ was used as a statistical performance measure of calibration.
3 Results and Discussions

3.1 Model Calibration

The hydraulic model calibration was made by comparing simulated value with measured values at the sampling points in the field. The pressure was measured in the distribution network using a portable pressure gauge at different nodes. The results of pressure measured and simulated by GIS integrated with WaterGEMS hydraulic model, as it was observed that RMSE is minimal. In addition, the hydraulic model in WaterGEMS
was calibrated in the Darwin calibrator feature and optimized until a great agreement with the field data ($R^2 = 0.93$), as can be observed in Fig. 6.

Once the hydraulic model was calibrated, it was verified using additional data sets measured in the field under different conditions. Verification was carried out by checking the pressure at the nodes. 13 measurements made from 3AM to 3PM were used in the study area; these measurements were different from those used in the calibration process. In the verification, the error in each of the nodes presented, has a coefficient of determination ($R^2$) of 0.97, which indicates a significant degree of linear dependence. As there are no significant differences, the hydraulic model represented in GIS integrated with WaterGEMS was validated (Fig. 7).
3.2 Analysis of Pressure in the Network

The analysis of the pressure distribution is a decisive parameter in water distribution network modeling. As a result of simulations carried out in the existing model, it was found that the pressure is found to be within the standard range of 15 to 70m H₂O head. All pressures at the nodes are distributed in the range of 11.004 mH₂O to 77.71 mH₂O, with few nodes are outside the standard pressures range of less than 15m and greater than 70 mH₂O (Fig. 8) at the time of peak hour demand.

As described in Fig. 8 above, 92.26% of consumption nodes have acceptable pressure limits between (15-70) mH₂O. Only 1.27% of the nodes are under pressure while the remaining are over pressure.

3.3 Analysis of Velocity in the Network

The analysis of the water velocity in the distribution made on the existing steady state models of tested water supply network showed that most pipes, its value are lower than the recommended. The result of velocity distribution shows that up to 17.35% of the network have low which may cause low water quality due to water stagnation, increase age of water, sediment accumulation and bacteriological growth in a pipe network. This covers 34 out of 196 pipes which had a velocity lower than 0.2m/s. A total of 162 pipes out of the 196 links accounting for 82.65% presented velocity between 0.2m/s to 2m/s, which is recommended range for water distribution network. According to the velocity result presented in Fig. 9, the velocity ranges of the pipes are divided into five intervals.

3.4 Developing Pressure Zone Boundaries

The result of the study indicates that the GIS integrated with WaterGEMS hydraulic model enhanced more detailed estimation of elevation contours and pressure contours. The pressure is strongly linked to the topography (Fig. 10) with a lower ground, the nodes are subjected to higher pressures whereas the high ground areas are subjected
to lower pressures. The high elevated area dwellers are getting less water due to their topographic location even though the demand is high. It is to be recalled that calibration was done for the areal demand allocated (Fig. 4). The high demands are indicating a high population density in that particular location. Whereas, the low demand locations are showing low population density. That means, the areal demand should be satisfied by the supply distribution system at a particular location. The high demand locations are subjected to high rate of consumption which might relieve the high pressure at topographically low locations and the opposite is happening in high elevated areas. However, for this particular study, demand and supply are well matching where the hydraulic

Fig. 9 Velocity distribution at steady state simulation

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performance ranges in terms of pressure as well as velocity are within the standard at the distribution system of the study area.

The integrated system can generate accurate, smooth contours for any variable including pressure, hydraulic gradient and flow directly on the map with a defined contour interval. The contours are mapped in the interval of 0.5 (Fig. 11) at the time of peak demand. Based on these pressure contours, it was found that 92.6% of the pressure in the system is within the standard from 15-70m head and only 1.27% of the pressure contours are below the recommended pressure.

**Fig. 10** Elevation contour map of Tulu Bolo town
Conclusions

In conclusion, the GIS based water distribution system modelling estimated the 92.6% of the pressure in the pipes is within the standard where as 82.7% of the water velocity in the pipes is within the standard. Hence, the implementation of the WaterGEMs hydraulic model integrated approach with GIS enabled to estimate the pressure and velocity of the system with better accuracy and this will be helpful for sustainable management of the water distribution system. Further studies recommended for georeferencing the water network geospatial databases like mapping household water connection points and its relational class between the parcels and water customer meters is required.

Fig. 11  Pressure contour map of nodes at maximum consumption hour

4 Conclusions

In conclusion, the GIS based water distribution system modelling estimated the 92.6% of the pressure in the pipes is within the standard where as 82.7% of the water velocity in the pipes is within the standard. Hence, the implementation of the WaterGEMs hydraulic model integrated approach with GIS enabled to estimate the pressure and velocity of the system with better accuracy and this will be helpful for sustainable management of the water distribution system. Further studies recommended for georeferencing the water network geospatial databases like mapping household water connection points and its relational class between the parcels and water customer meters is required.
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**Declarations**

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**Consent to Participate**  Not applicable.

**Consent to Publish**  We both the authors of this research will provide full consent for the publication of this manuscript to the journal of water resources management.

**Competing Interests**  As far as we know, no competing interests on this article

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