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Modelling of Water Distribution Network for Hayin Banki, Kaduna State

[1]Garba H and [2]Abiola. A

[1, 2] Department of Civil Engineering, Nigeria Defence Academy, Kaduna, Nigeria.

Corresponding Author: * hgarba@nda.edu.ng; Tel: 08020346775

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Abstract

Water distribution systems are designed to adequately satisfy the water requirement for domestic, commercial industrial and firefighting purpose. A spatial database of the water distribution systems (WDS) for Hayin-Banki was created in a Geographic Information System (GIS) environment (ArcGIS), drawing inputs data from water supply and demand. Environmental Protection Agency Network (EPANET, 2.0) was used to analyze the WDS to explore its reliability in current and future scenarios. Mapping of the existing 12.270 km long distribution network revealed that the total length of ductile iron pipe (DIP) is 11.12 km and asbestos cement (AC) pipes is 1.15 km. Running the analysis identified supply gaps, which includes deficiencies in the distribution system (small diameters pipes, system losses) resulting to negative and very small pressures. Running simulations with EPANET and geospatial techniques was used to solve the identified deficiencies.

Keywords: *ArcGIS* EPANET, Global Mapper, GPS, population scenarios, Water Distribution System

Introduction

Water is vital for man's existence and without it; there would be no life on earth. As a resource to any nation, it should be well planned, developed, conserved, distributed and managed. Its infrastructure should be properly maintained to avoid future water problems. The global water requirement is on the increase and the per capita water consumption is also on the increase due to the increase in population and civilization(Audu and Anyata, 2010; Audu and Ehiorobo, 2010; Audu and Edokpia, 2010). The world's population is expected to grow exponentially from about six billion in 2000 to eight billion by 2025, 90 percent of this population increase will occur in urban areas intensifying the demand for potable water to satisfy human needs.(Lacquemanne, 2000).

In 2015, WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation; WASH Watch. Retrieved 21 March (2017), reported that 67% of the total population had access to "at least basic water supply. This was 82% of the urban population and 54% of the rural population, also in the report about 60 million people lacked access to "at least basic" water, for sanitation, only 33% of the total population having access to "at least basic" sanitation. This was 39% of the urban population and 27% of the rural population. Cullen (2005) , reported that approximately 122 million people still lacked access to "at least basic" sanitation due to challenges associated with data collection and distribution. These challenges have continued to demand innovation and state- of- the- art technology needed for drastic changes in the location, planning, collection, distribution and management of water infrastructure (Cullen, 2005, Audu and Ehiorobo, 2010).

The increase in population in Nigeria, has led to increase in water demand without corresponding growth in water distribution system, though private boreholes which do not require treatment abound, water borne diseases are on the increase due to low pressures in the distribution systems (Izinyon, 2007).

Study Area and Data used

Hayin Banki a suburb of Kaduna metropolis (Figure 1), is located in Kaduna North Local Government area and lies between coordinates Latitude: 10° 33' 12" N. Longitude: 7° 26' 29" E. Lat/Long and elevation of 631 meters above sea level.

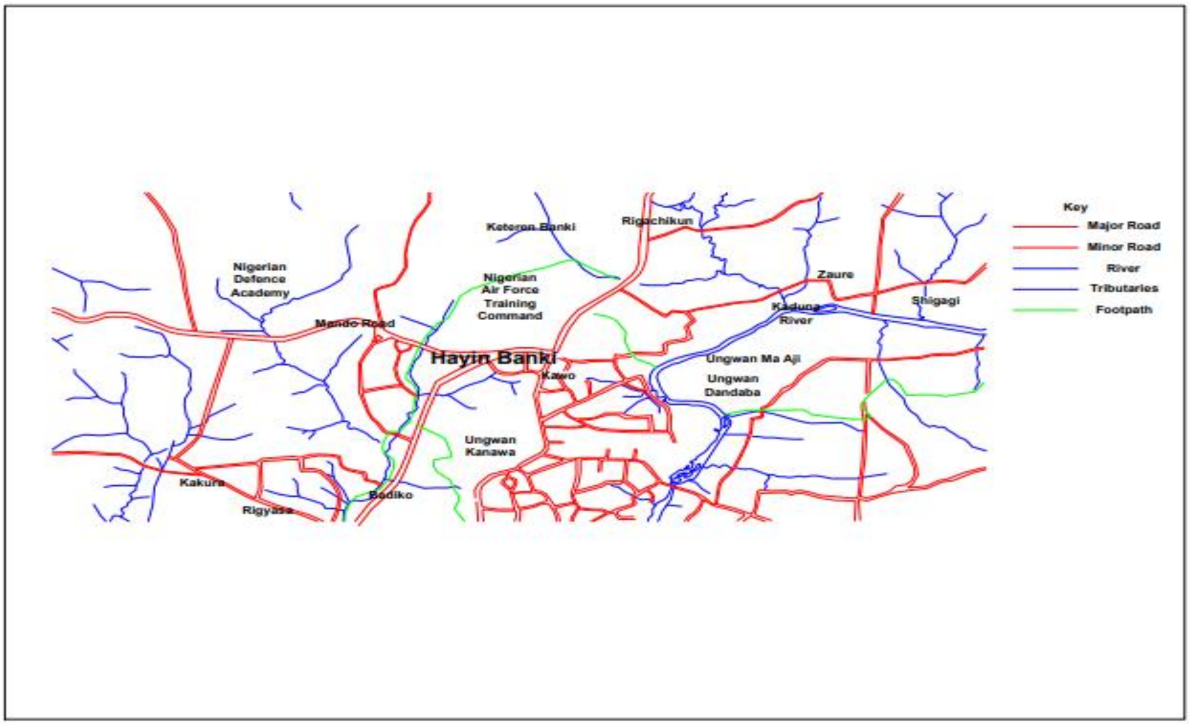

Figure 1: Study area Hayin Banki, Kaduna

Materials and Methods

Data used (spatial and non-spatial data)

Water supply distribution network map

The water supply network map of Hayin Banki sourced from Kaduna State Water Cooperation (KASWAC), are hard copy maps, Computer Aided Design (CAD) files, prepared in portable document format (PDF) files were input data used for the analysis.

Remote sensing data

Remote sensing data of the Nigeria Remote Sensing Satellite (IRS)-P34 satellite image (10.08), conducted in 2021) was sourced from Google Earth, was created.

Ancillary data

A Digital Elevation Model (DEM) of Hayin Banki was obtained using Blue Marble Geograhics (Global Mapper: v19.0.0) (Figure 2). The non-spatial data used for the study are Census (1991) data for Hayin Banki area, existing water supply network parameters of distribution main from NDA surface tank, reservoir demand capacity, length, Size and material of distribution pipelines were obtained from Kaduna State Water Cooperation (KASWAC)

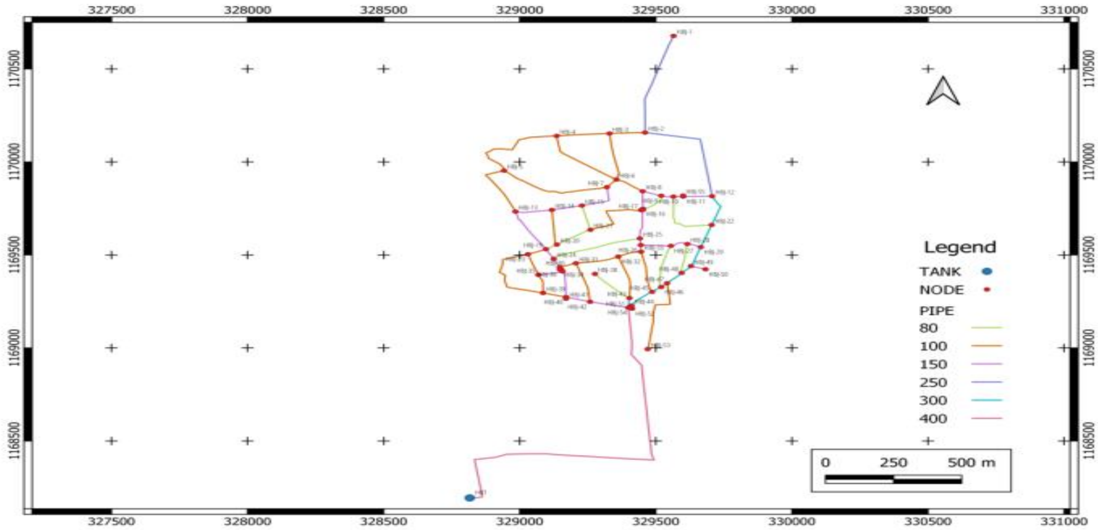

Figure 2: WDS of Hayin Banki

Data Processing

Geospatial

Water Distribution Network (WDN) layers were established in the GIS (ArcGIS) environment with high resolution images in the background. Ground coordinates of the WDN was obtained using GPS, and the diameter and height of Elevated Water Tank EWT needed for hydraulic design were determined.

A DEM of the Hayin Banki was produced using contours at 1-m interval and spot levels from Global Mapper. The pipe locations, depth and diameter were verified and updated using the hard copy, Computer Aided Design (CAD) drawings from the Water Cooperation and GPS. The water demand at each node was assigned by constructing polygons across each node.

Creating a GIS database of water utilities

The high-resolution images from Google Earth extracted using Google Earth Pro as well as the ArcGIS were geo-referenced in Universe Transverse Mercator (UTM) projection system with WGS84 datum and UTM Zone 32 N. Later, the water supply network map was created in GIS environment with high-resolution image in the background. The road layer was also overlaid to get a preliminary idea of the correctness of the map, as all water pipelines should coincide with the road network. After all the data were geo-referenced, separate vector layers of tanks, nodes, and pipes were created, containing point and line data and stored in a file geo-database. These data were spatially adjusted wherever they did not correctly overlay the roads.

It was ensured that not even a single link was left un-jointed to another and every node was connected to a link. Therefore, in order to create a WDN, all the topological errors like undershoot, overshoot, overlap, multipart features, duplicate features, etc. were removed using the topology tool the ArcMap 10.1. After the removal of errors, the data were exported as shape files (.shp) format so that they could be taken as input in EPANET using Network Survey Manager.

Water utility and GPS survey

All essential parameters, such as diameter and height of EWT, as required for hydraulic design, were collected with the help of a GPS. The pipe distribution network was digitized and all the attributes such as pipe diameters and material were manually entered. All this information was reproduced in GIS by creating a spatial geodatabase and then attaching their non-spatial attributes to them.

Digital Elevation Model (DEM) generation

The study of a water supply system requires the detailed topography of the area, i.e., reduced level (RL) of roads and road crossings. The DEM of Hayin Banki was generated using contour lines of 1-m interval sourced from Advance Space borne Thermal and Emission and Reflection Radiometer (ASTER) and spot levels obtained by using Global Mapper.

Population Projections

Population projection is done to ascertain the future demands, the current (2022) and future population (2027) scenarios were created using the base population for the census year 1991 (Table 1) to estimate the water supply– demand scenario for the study area.

Table 1 Population Growth

S/No	Population Growth Rate in locality (%)	1991 population	2022 population
1	**3.0**	**17.35**	**43.446**

Hydraulic parameters

Spatial database and their attributes were created and given specifications for the various hydraulic parameters, also physical and non-physical components involved in a water distribution system (WDS) and their attributes attached serve as input into the EPANET model.

Hydraulic Modeling

The details about elevation, level, diameter, and capacity of the storage tank as obtained were fed into the EPANET model and a 24-hour extended period simulation was run over the network, pressure at all nodes and velocity in all the pipes, were analyzed for a 24-hour period at 1-hour intervals.

Hydraulic Simulations

EPANET hydraulic model was used for simulating the piped potable (WDN) of Hayin Banki. The basic principle on which the model's algorithm runs is 'hydraulic balancing' of network using 'hybrid nodeloop' approach so that flow continuity and head loss continuity conditions are satisfied at every iteration. The algorithm is termed 'gradient algorithm' and its calculations are based on the Newton-Raphson method, (Todini and Pilati 1987). The following system of equations is solved by the computer program to arrive at the final results after each iteration in the model (Rossman 2000; Garg 2010):

Hazen–Williams equation (Williams & Hazen 1933) for calculating head loss in pipes:

$$S = \frac{h_f}{L} = 10.67Q^{1.852} \times d^{4.870} \qquad (1)$$

Water Demand

The water demand at each node was assigned using the area from the thiessen polygon and the population density map was converted into raster format. Using extract values to points function in ArcMap, these population density values were extracted to each node. The area was calculated for every Thiessen polygon using the calculate geometry tool; thereafter, these areas were attached to their respective nodes using spatial join tool (Figure 5).

Once area and population density attributes were obtained in a single shapefile, these two were multiplied together to get the population for every node. Later, this population was multiplied by 100 liter per capita/ day (LPCD) and divided by 1000 to give meter cube per day (m3/d) for the sake of ease while feeding it into the model. The total demand in m3/d was divided by the total of the Thiessen polygon to get the control demand; thereafter, the control demand was use to multiply each node area to get the per capita demand for each node in m3/d. Table 2 indicate that the water demand estimated is 8,689m^3/d in 2022 and 10,073m^3/d in 2027, respectively. This water demand gap, is deficient by (1,424 m^3/d) for the year 2027, encompassing 65%, of the demand (Table 2)

Table 2. Water Demand

S/No	Main reservoir serving locality	Water demand estimate (m^3/d)	
		2022	**2027**
1	**State house**	**8,689**	**10,073**

Mapping and updating existing WDS

All the data pertaining to pipelines were brought into GIS from CAD files, PDF files, and hand-drawn maps. Table 3 shows a summary of the diameter wise-lengths of all the pipelines currently supplying water to the Hayin Banki. It can be seen that the total length of the existing distribution system is nearly 12.270 km; of this, the lengths of ductile iron pipe (DIP) are 11.12 km and asbestos cement (AC) pipes are 1.15 km. The variable diameter pipes which constitute the WDS network is presented in Table 3. After assignment all the spatial and non-spatial parameters of all the elements involved like pipes, tanks, and reservoirs, the final GIS-based WDS of Hayin Banki was drawn, and the results shows the complete potable WDS of Hayin Banki, along with various input data layers such as, pipe material, pipe diameter, and full WDS system. Pipes locations were verified and updated at certain points using GPR. This helped in verifying the location, depth, and diameter of the pipelines. The percentage extent of various pipe sizes (80mm, 100mm, 150mm, 250mm, 300mm and 400mm) is 11.69%, 33.77%, 35.06%, 2.60%, 15.58% and 1.30%, respectively, is presented in (Table 4).

Results and Discussions

WDS analysis in EPANET

A 24-hour extended period simulation was run over the network, with total of 55 junctions, 77 pipes, and 1 storage tanks (Fig 2). It was observed that the existing WDS is plagued with several shortcomings, most striking of which is the diameter of the distribution main all over the network. However, some parts of the system are old and the pipe diameter is low, which results in building of negative pressure and insufficient hydraulic head conditions in the network. There exist situations of negative pressure and very low pressure in almost 65% of the network (Figure 3). The greatest problem persists between 5 a.m. and 7 a.m. when the water demand is at its peak (Figure 3, 4, 5 and 6). These negative pressures gradually reduce as peak demand hours pass and the system becomes stable, (Figure 7). Negative pressures were observed at 22 nodes, and these locations exist in the central, north, northeast and northwest part of the network (Figure 5), and negative pressures due to smaller diameter of the pipe was rectified in the model by hypothetically increasing the diameter. The negative pressure (Figure 7, 8), simulation was solved by increasing the pipe diameter on the distribution main.

Table 3 Summary of existing pipelines

			Length(km)	
S/No.	**Diameter (mm)**	**Material**	**DI**	**AC**
1	150	DI	0.113	0
2	150	DI	0.036	0
3	150	DI	0.036	0
4	300	DI	0.126	0
5	300	DI	0.042	0
6	150	DI	0.015	0
7	150	DI	0.011	0
8	300	DI	0.029	0
9	150	DI	0.144	0
10	80	AC	0	0.047
11	150	DI	0.006	0
12	150	DI	0.106	0
13	100	DI	0.087	0
14	80	AC	0	0.134
15	100	DI	0.063	0
16	100	DI	0.005	0
17	150	DI	0.056	0
18	150	DI	0.008	0
19	100	DI	0.054	0
20	300	DI	0.010	0
21	300	DI	0.010	0
22	250	DI	0.536	0
23	100	DI	0.131	0
24	100	DI	0.195	0
25	100	DI	0.426	0
26	100	DI	0.420	0
27	100	DI	0.299	0
28	100	DI	0.340	0
29	100	DI	0.252	0
30	100	DI	0.116	0
31	150	DI	0.176	0
32	150	DI	0.135	0
33	150	DI	0.237	0
34	100	DI	0.188	0
35	80	AC	0	0.147
36	150	DI	0.156	0
37	150	DI	0.095	0
38	80	DI	0.107	0
39	100	DI	0.011	0
40	80	DI	0.285	0
41	150	DI	0.072	0

42	150	DI	0.046	0
43	300	DI	0.169	0
44	150	DI	0.053	0
45	150	DI	0.067	0
46	150	DI	0.111	0
47	80	DI	0.228	0
48	150	DI	0.036	0
49	80	AC	0	0.340
50	150	DI	0.060	0
51	100	DI	0.089	0
52	100	DI	0.220	0
53	100	DI	0.230	0
54	80	AC	0	0.182
55	300	DI	0.052	0
56	300	DI	0.107	0
57	300	DI	0.077	0
58	80	DI	0.161	0
59	300	DI	0.050	0
60	300	DI	0.109	0
61	100	DI	0.409	0
62	300	DI	0.007	0
63	150	DI	0.092	0
64	100	DI	0.215	0
65	100	DI	0.161	0
66	150	DI	0.139	0
67	150	DI	0.091	0
68	100	DI	0.101	0
69	100	DI	0.396	0
70	100	DI	0.117	0
71	100	DI	0.071	0
72	150	DI	0.050	0
73	250	DI	0.516	0
74	100	DI	0.007	0
75	150	DI	0.005	0
76	100	AC	0	0.298
77	400	DI	1.747	0
	Total (km)		**11.122**	**1.148**
	% of Total Pipe Length		***90.64***	***9.36***

Negative pressures were observed at 22 nodes, and these locations exist in the central, north, northeast and northwest part of the network (Figure 5), and negative pressures due to smaller diameter of the pipe was rectified in the model by hypothetically increasing the diameter. The negative pressure (Figure 7, 8), simulation was solved by increasing the pipe diameter on the distribution main.

According to the CPHEEO (2005) guidelines, the velocity in pipes should be between 0.6 and 2.0 m/s subject to minimum pipe diameter of 80 mm. At several places, this criterion has been exceeded during the peak hours in the network. There are 46 locations where this phenomenon is happening. Few places where velocity was too low included the pipes which have to carry water from lower to higher elevations. Simulation results showing the stable network is in Figure 9.

Table 4 Diameter (mm) and (% of pipes)

S/No.	Diameter (mm)	Percentage %
1	80	11.69
2	100	33.77
3	150	35.06
4	250	2.60
5	300	15.58
6	400	1.30

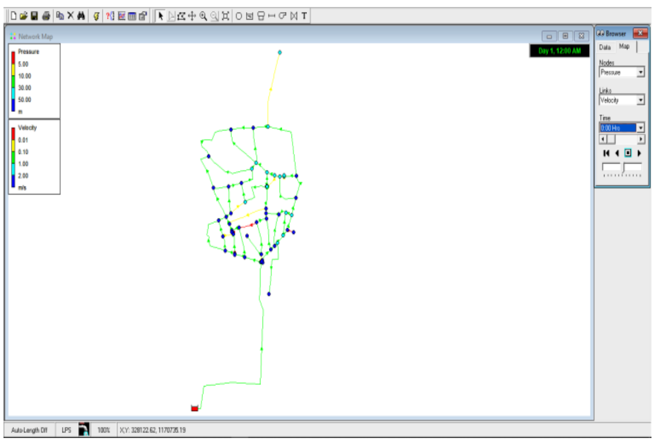

Figure 3: WDS simulation results showing Pressure and velocity at morning (04:00 hr)

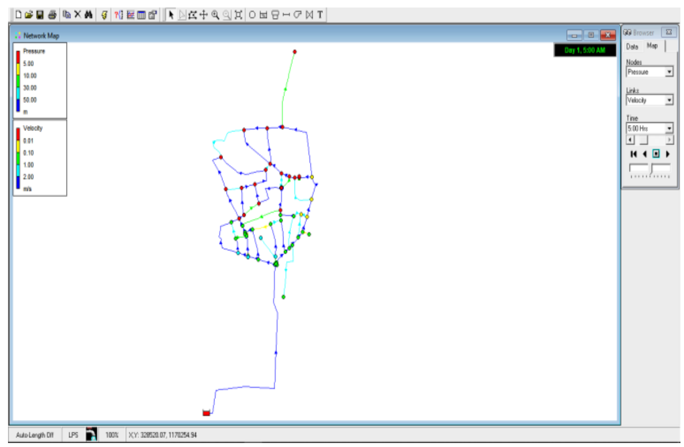

Figure 4: WDS simulation showing Pressure and velocity at morning (05:00 hr).

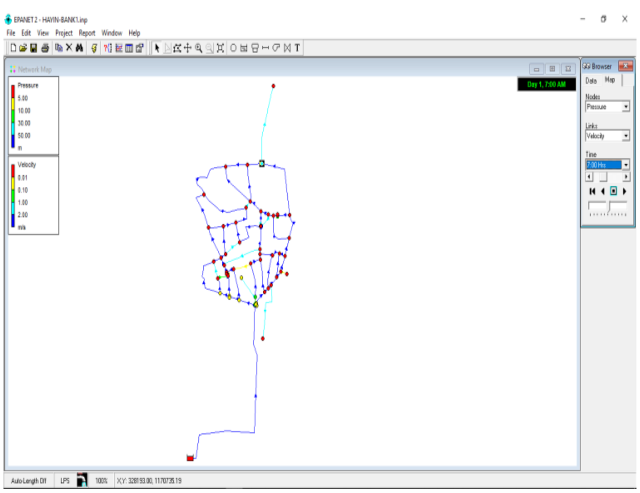

Figure 5: WDS simulation results showing Pressure and velocity at morning (07:00 hr)

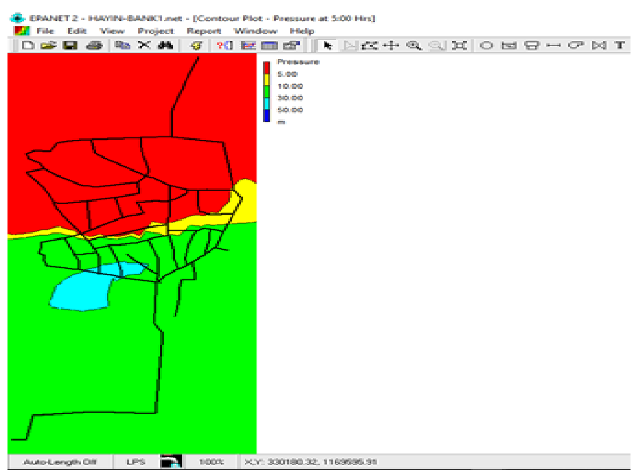

Figure 6: WDS simulation results showing Pressure and velocity at morning (05:00 hr).

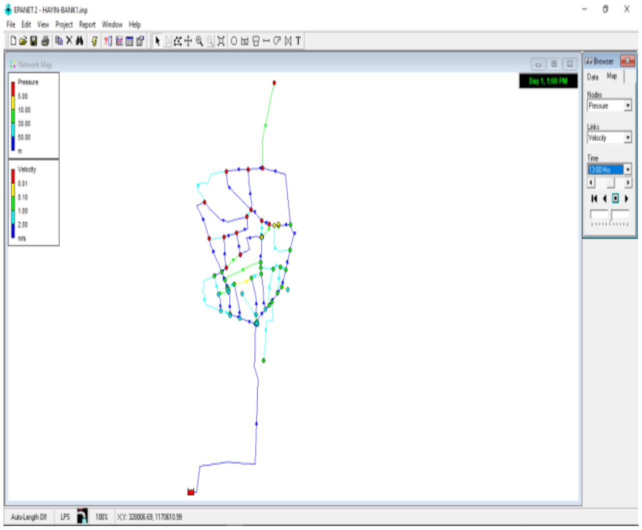

Figure 7: WDS simulation results showing and velocity (13:00 hr).

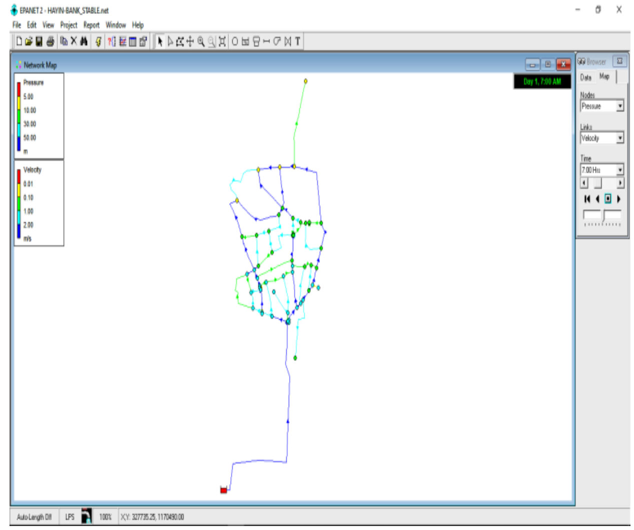

Figure 8: WDS simulation showing Pressure Stable network at peak hr.

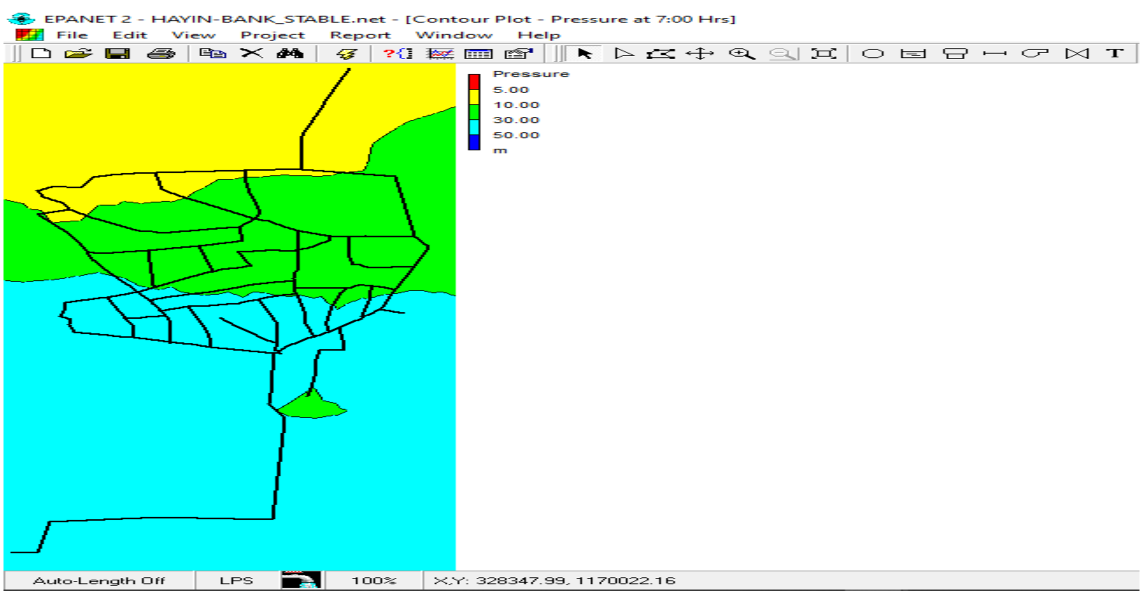

Figure 9: Sample WDS simulation results showing stable network at peak hr.

Conclusion

A spatial data base of an existing water distribution system (WDS) for Hayin Banki was created in a GIS environment (ArcGIS). Input data into EPANET 2.0 software was used to analyze the WDS. Running the analysis identified supply gaps, which includes deficiencies in the distribution system (small diameters pipes, system losses) resulting to negative and very small pressures. Running simulations with EPANET and geospatial techniques was used to solve the identified deficiencies.

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