Civil and Environmental Engineering
Vol. 20, Issue 2, 1095-1106, DOI: 10.2478/cee-2024-0079

PREDICTIVE MODELING THE TURBIDITY RESPONSE IN AL-SARAY WATER DISTRIBUTION NETWORK IN NAJAF GOVERNORATE/ MIDDLE OF IRAQ, USING PODDS MODEL

Zahraa H. ABED[1], Hayder M. JASEM[2,*], Hayder S. MOHAMMED[3]

1 Dept. of Civil Eng., College of Eng., Univ. of Basrah, Basrah, Iraq
2 Dept. of Structures and Water Resources, College of Eng., Univ. of Kufa, Najaf, Iraq
3 Dept. of Structures and Water Resources, College of Eng., Univ. of Kufa, Najaf, Iraq
* corresponding author: Hayderm.almosawey@uokufa.edu.iq

Abstract

Reducing water turbidity is one of the main issues the water industry is currently experiencing. The ability to predict the spatial probability and intensity of discoloration events in distribution systems can lead to the adoption and improvement of proactive operation and maintenance strategies to reduce turbidity. The main objective of this study is to forecast Using the Prediction of Discoloration in Distribution Systems (PODDS model), simulate the turbidity response in the Al-Saray water distribution network caused by higher flow rates and a change in the daily demand pattern for water consumption. The work covered AL -Saray water distribution network. with took into account the two feed flowrate (FFR) values of the AL-Saray water network, which were (522 and 5870) m^3/day. The turbidity response was observed to be low when daily flows were supplied to the network, but it increased as the flow increased. The maximum turbidity response was observed when water was fed into the Al-Saray water network at a flowrate of 5780 m3/day. the material layers are conditioned to daily flow, or shear stress. However, when the flow increases due to an increased demand for water, the fluid's shear stress exceeds the material layers' shear strength, which leads to the material becoming mobilized.

Keywords:

Turbidity
Modelling
PODDS Model
Water distribution system
discolouration

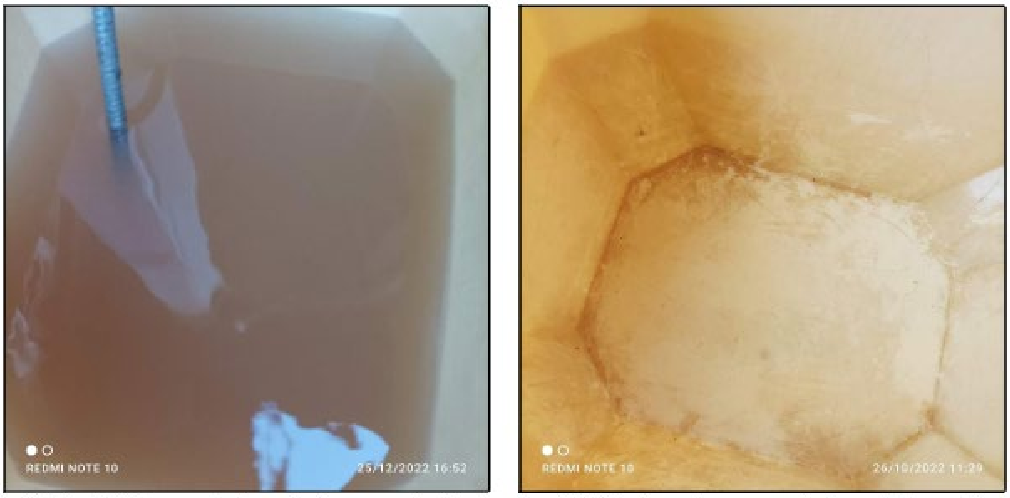
1 Introduction

Distribution networks for potable water are designed to carry only dissolved stuff, not particles of suspended solids. All suspended solid particles cannot, however, be eliminated from the raw water. Water discoloration is mostly caused by turbidity, which is a general indicator of the number of suspended particles in water. However, 5 NTU is the threshold at which turbidity may be seen with the unaided eye [1].

The dispersal of collected particulates from distribution networks is associated with turbidity. Particles tend to gather then take up residence in any pockets or at the bottom wall, which could include pipe bends, T-junctions, dead ends, or a combination of these. Turbidity is caused by these particles re-entering the system during periods of extreme turbulence, such as flushing, pipe bursts, etc., or any irregular flow [2] These particles arise from a range of sources due to their varying sizes and densities. The distribution systems get a lot of tiny particles and dissolved chemicals from different sources during the bulk flow. These materials and particles have the capacity to come together and create material layers that adhere to the interior surfaces of pipelines [3]. Over the past two decades, a number of scientists have developed conceptual models to describe how suspended particles in water networks distribute and cause turbidity. Most of these models use the term "discoloured water" to refer to turbid water. Two common causes of discoloured water in water networks are corroded pipes and poor-quality water fed into the system. The first phenomenon is important when the network pipes are made of materials susceptible to corrosion, like iron or steel. The second phenomenon can cause discoloured water in any water network if the water is given to it from a mediocre water treatment facility.

An overview of earlier models pertaining to turbid or discoloured water in water distribution systems is provided here Boxall et al. [4] performed a mathematical study of the relationship between the hydraulic forces generated within distribution networks and the particles of the size found to predominate in discoloured samples of water. They concluded that additional forces and mechanisms are necessary to prevent particle movement. A turbidity current was suggested by Boxall and Saul [5] as a means of estimating the materials that could be generated at the pipe wall. They developed a semi-empirical model named Prediction of the discoloration Occurrence in Distribute Networks (PODDS). Layers of material whose shear force is dictated by the wall stresses (WSS) of the fluid flow at the pipe surface simulate material buildup. Melbourne, Australia's water distribution network was used to evaluate a semi-empirical predictive model (PODDS model) by Boxall and Prince [6] The findings demonstrate that the model may be adjusted to replicate the turbidity response observed in actual systems as a result of modifications in hydraulic conditions for discoloration issues caused by clay. Husband et al. [7] reported on laboratory results that fine particle conditioned by the system's usual daily flow patterns were eroded as a result of changes in shear stress at the pipe wall due to a change in demand such as a burst or the opening of a fire hydrant. Ryan et al. [8] developed the empirical Particle Sediment Model (PSM), which is able to forecast the mobilization and deposition of particles on pipe walls. This hypothesis states that the van der Waals force allows particles to adhere to the pipe walls of their experimental system. The addition of a surface adhesion force to the PODDS model showed a relationship between the buildup of material layers and the specific shear strength. Prior to altering the pump settings to shift to a lower fluid velocity, Ryan et al. used a small pipe loop facility to maintain a particle suspension at a velocity of (0.6) m /sec for two hours. Conditioning velocities of between 0.07 and 0.3 m/sec were used for the tests. Husband and Boxall (2010) measured variations in water turbidity caused by changes in flow velocity while flushing pipes of varying diameters and materials (cast iron and plastic) in the United Kingdom. This allowed them to validate the PODDS model. The authors discovered that there are variations between cohesive layers created in plastic pipes and those formed in iron pipes, and that the primary source of water turbidity in distribution systems is the resuspension of cohesive layers adhering to pipe walls. The authors of the study reported that corrosion of pipes and fittings or suspended particles entering the distribution system from the water source are the primary causes of cohesive layer formation on pipe walls. Van Thienen et al. [10] created a theoretical model that takes into account the movement of turbulence to represent the radial movement of suspended substances in water distribution systems under varied hydraulic circumstances. They showed that the impact of turbulence movement on the radial transport of particles is significant for particles having a diameter greater than 50 µm. Also, they pointed out that this impact is significant in water transmission pipes rather than distribution pipes. Husband et al. [11] investigated a turbidity (discoloration) problem, simulating 18-month turbidity data from a 4 km main trunk using four EPANET MSX extended-period model fittings. Data from measurements indicate hydro conditioning as an active form of mitigation and frequent regeneration of discoloration risks. Sunny et al. [12] Present a validated modelling capability for the Variable Condition Discoloration Model (VCDM), which tracks long-term turbidity behaviour while concurrently simulating material mobility and accumulation processes. The scientists found that the VCDM can track long-term material motion and that accumulation behaviour occurs in big diameter trunk mains dependent on applied hydraulic forces. The authors also showed how proactive management for hydraulic-based applications, such routine maintenance scheduling, is made possible by tracking pipe wall layer state, specifically the Accumulation functionality.

Figure1 illustrates the excessive turbidity tap water supply that the residents of the Najaf governorate, particularly those living in Kufa city, are experiencing. This is because the effluent flowrates from treatment plants were boosted by Najaf Water Directorate to make up for the constraint of water supply brought on by the governorate of Najaf's population growth. This was carried out without maintaining the water quality within the advised ranges or enlarging the current water distribution networks to handle the increase in flow rate. The main objective of this study is to forecast Using the PODDS model, simulate the turbidity response in the Al-Saray water distribution network caused by higher flow rates and a change in the daily demand pattern for water consumption.



(a) Turbid tap water in a bathroom plastic pan

(b) Sediments accumulation at the walls and bottom of a bathroom plastic pan

Fig.1: High turbidity tap water in the governorate of Najaf presented visually

2 Methodology

2.1 Study area

Al-Saray district is one of the important districts in the city of Kufa. The city of Kufa is one of the Iraqi cities located in the east to the north of Najaf Governorate (middle of Iraq). Al-Saray is located at latitude 32˚ 2' 29.85" and longitude 44˚ 23' 59.82" east. One of the water distribution networks in the city of Kufa is Al-Saray network; raw water for this network is taken from the Shatt Al-Kufa River, which is one of the branches of the Euphrates River. The Kufa city network receives its water supply from the old Kufa water treatment plant. Fig. (2).

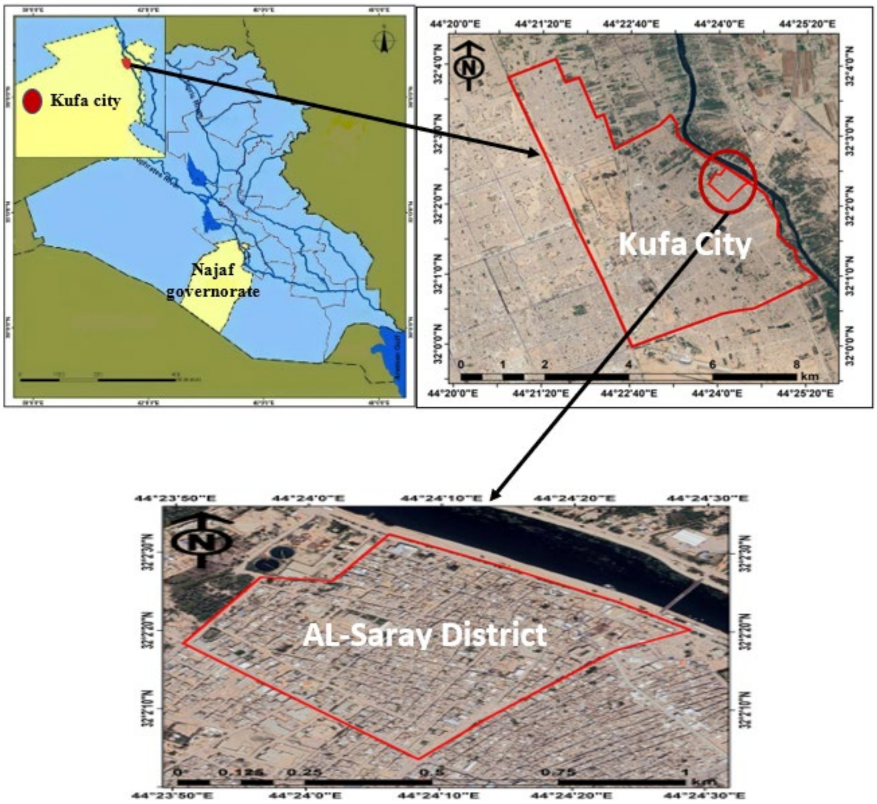


Fig. 2: Al-Saray district location [13].

2.2 Prediction of Discoloration in Distribution Systems (PODDS)

The Pennine Water Group (PWG) at the University of Sheffield in the UK developed PODDS, a computer-based discoloration model, as a research tool. The model is intended to work as a water quality module, so it may be connected with any hydraulic modelling program. This work was done in compliance with the funding standards for research on EPANET, freeware available for download from the US EPA. EPANET is a hydraulic analysis application with an extensive timeline and a powerful graphical user interface. Two continuing PODDS projects are being worked on by the Pennine Water Group at the University of Sheffield: one is enhancing empirical model parameters, which is currently focused on trunk mains, and the other is integrating the PODDS approach into feasible operation and maintenance policies. Since material regeneration rates dictate the prerequisites and return intervals for routine cleaning operations and, consequently, the efficient management of pipe assets, they are also drawing increased attention in study.

PODDS is predicated on the idea that cohesive material layers that accumulate on the walls of pipes within distribution systems become mobilized and cause discoloration events. These layers, according to the model, are "conditioned" by the regular daily flow through each pipe in the system; therefore, they do not become mobilized when exposed to the diurnal pattern of daily flow and no discoloration is anticipated. A discoloration event may arise from layer erosion brought on by an increase in the regular flow, such as that caused by unusual demand, such as a burst event or operational activities. The discoloration that ensues is determined by the hydraulic force that mobilizes and the strength and turbidity potential of the layer as described.

2.2.1 PODDS equations

The foundation of the PODDS model is the "balancing" of the shear stress forces produced by the system hydraulics with the cohesive layer strength at the pipe wall. They are as given below provide specifics on the model's mathematical development [4]:

Hydraulic shear stress can be calculated from any hydraulic model, Equation (1)

$$\boldsymbol{\tau}=g\rho\,\frac{D}{4}\,S_0 \tag{1}$$

Three empirical parameters are used to describe the possible relationships between layer strength and turbidity potential of the cohesive layers, see Equation (2)

$$\tau'_s=\frac{C^b-C_{max}}{K} \tag{2}$$

When a mobilizing or disturbing hydraulic force is applied, material from the cohesive layers is mobilized, as described by equation (3). The model includes two empirical factors to relate the material release to the excess shear stress: a gradient term (P) and a power term (n):

$$R=P\,(\tau_a-\tau'_s)^n \tag{3}$$

Equation (4) can be applied to calculate the incremental variation in turbidity caused by this erosion by multiplying R by the affected pipe surface area (A_s) and dividing by the flow rate Q.

$$\Delta N=\frac{R\,A_s}{Q} \tag{4}$$

while the change in turbidity potential and hence the strength of the layer can be evaluated from Equation 5.

$$\Delta C_e=R\Delta t \tag{5}$$

Where:

$\boldsymbol{\tau}$- is boundary shear stress (Nm^{-2})

ρ- density (Kgm^{-3})

g- acceleration due to gravity(ms^{-2})

D-pipe diameter (m).

S_0-hydraulic gradient

τ'_s -is the current layer strength (Nm^{-2})

C- turbidity potential (NTUm).

K-Gradient describing relationship between yield strength and ability of cohesive layer to increase turbidity ($NTUm^3\,N^{-1}$).

C_{max}- Maximum turbidity (discolouration) potential (NTUm).

b-Power term to allow for nonlinear forms describing the relationship.

R- Rate of supply ($NTUms^{-1}$)

P- Coefficient of eroding force ($NTUm^3\,N^{-1}s^{-1}$).

$(\tau_a-\tau'_s)$- Excess shear stress (Nm^{-2})

n - Power term to relate the release of material to the excess shear stress.

A_s - Pipe surface area (m^2).
Q- Discharge (m^3 s^{-1}).
ΔN-the increase in turbidity.
ΔC_e- the amount of material eroded from the corrosion layer in the time step Δt.

2.3 Hydraulic Modelling of Water Network

PODDS is integrated as a water quality component of EPANET by means of the substance tracking, transport algorithms, and EPANET hydraulic solution. A calibrated hydraulic model that incorporates such a modelling method can be used to simulate the discoloration risk (potential and impact) that is provided by different network locations and hydraulic circumstances. The model can be used to schedule preventative maintenance procedures, including cleaning systems to reduce the possibility of discoloration problems, once it has been calibrated.

The US Environmental Protection Agency developed the EPANET software. This computer application simulates in detail how hydraulic systems behave and how water quality is in pressured pipe networks. Pipes, nodes (connections between pipes), pumps, valves, and reservoirs or storage tanks make form a network. EPANET forecasts the water flow rate and, consequently, the flow velocity in each pipe, the pressure at each node, and the height of the water in each tank over a simulation period that is discretized into many time steps [14].

2.3.1Data Collection

The layout of a water network is a prerequisite for conducting a hydraulic analysis of that network. Fig. 3 displays the Al-Saray network's configuration, which was provided by the Najaf Water Directorate's GIS department. Additionally, the following information is needed in order to use EPANET software to perform hydraulic simulation of the Al-Saray water network:

1) Number of nodes and pipes in the network: According to the Al-Saray network's architecture plan, there are 265 pipes connected to 171 nodes in the network (see Fig. 4).
2) The dimensions of every network pipe, including its length and diameter, were measured and taken from the layout plan. Additionally, Google Earth software was used to verify the pipe lengths.
3) Network node coordinates: For this study, the network layout plan provided the network node coordinates, while a Google Earth map was used to determine the heights.
4) Network node elevations: A Google Earth map was used in this study to determine the node elevations.
5) The way the network operates: According to the Najaf Water Directorate, Al-Saray Network's operation—which involves supplying water to the network—operates continuously around the clock.
6) Locations of water sources and their flow rates: The Old Kufa WTP serves as the water source for the Al-Saray water network. The Old Kufa WTP's feed flow rate fluctuated based on how many high lift pumps were in use. In the study, three feed flowrates (4500 and 7500 m^3/hr) were used to replicate the flow in the Al-Saray water network.
7) Water demand flow pattern: A fluctuating water demand pattern was used to obtain a trustworthy depiction of the hydraulic state in the Al- Saray water network. The variance in demand factors displayed in Fig. 5 was utilized to obtain this pattern. It is noteworthy to note that the demand pattern depicted in Fig. 5 was derived from earlier research, as the Najaf governorate lacks meters to accurately measure water demand.

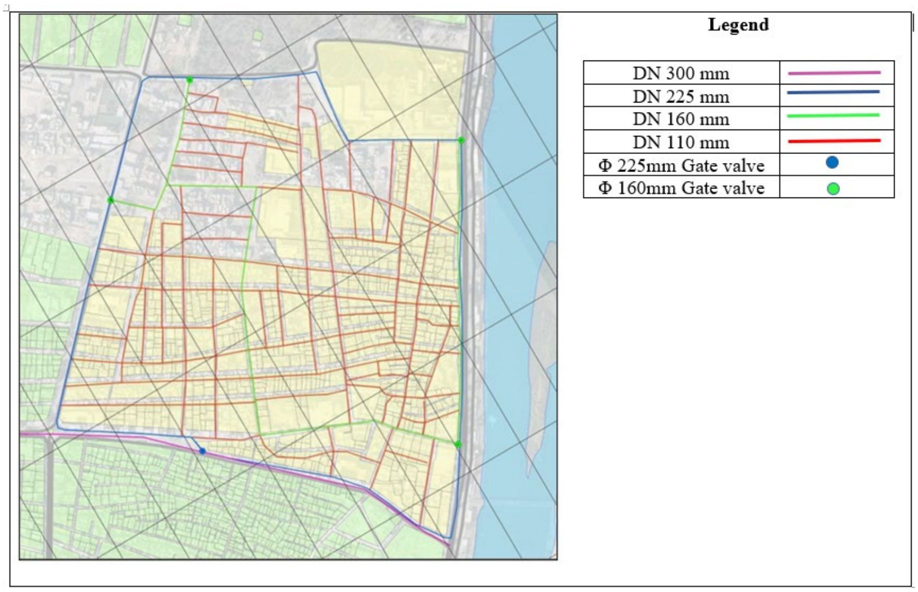


Fig. 3: The Al-Saray water network's layout

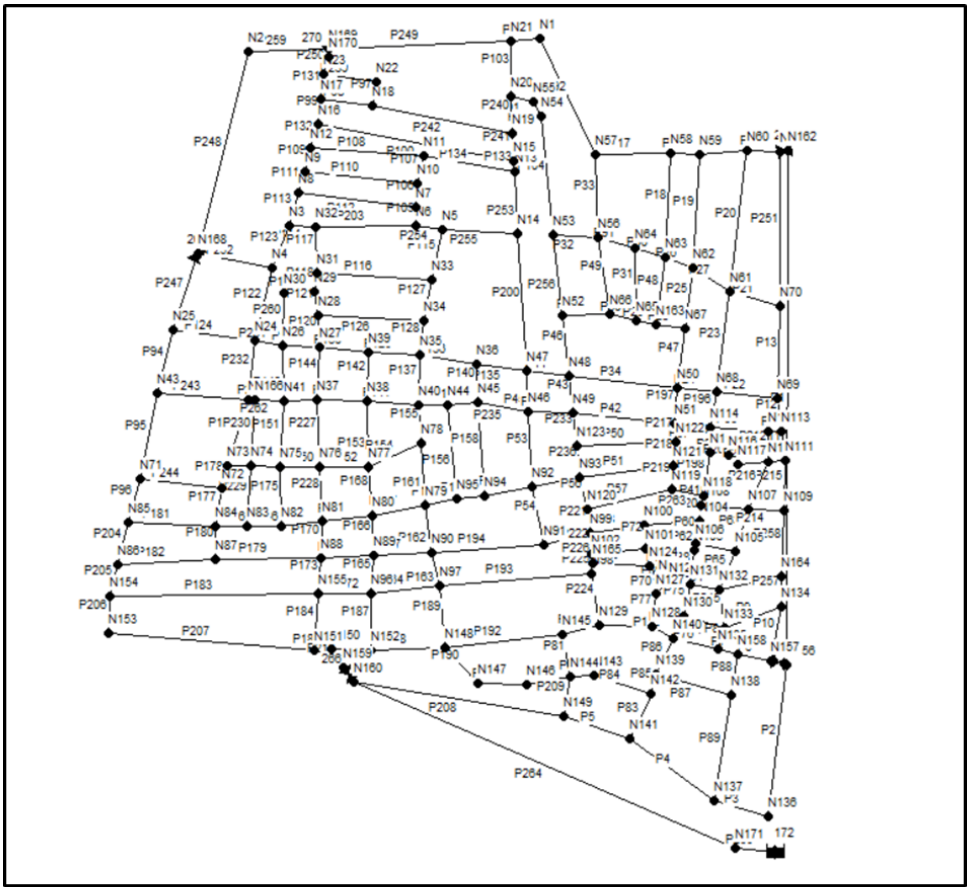


Fig. 4: AL-Saray water network layout with EPANET software

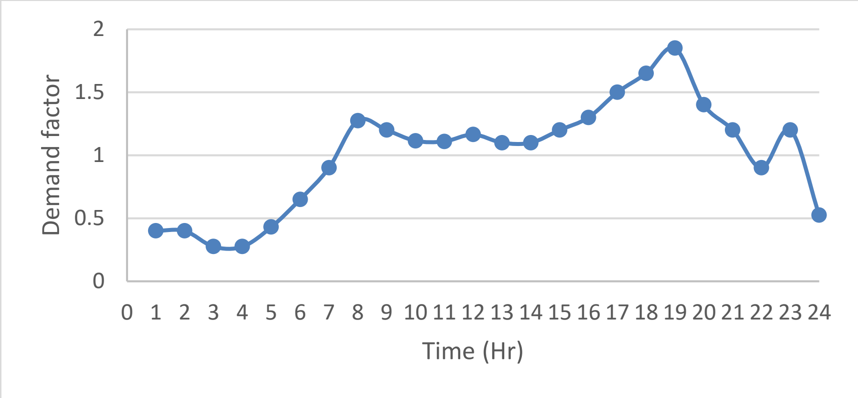


Fig.5: Demand curve for daily consumption of water [15]

2.3.2 Assumptions

When hydraulic modelling the Al-Saray water network, the following presumptions were considered.

1) It was stipulated that the Hazen-Williams coefficient "C" values for PVC pipes and ductile iron pipes were 150 and 140, respectively.
2) There is a flow control valve.
3) Every network demand node receives an equal amount of the network feed flowrate.

2.3.4 Nodes input data

Al-Saray water network comprises 171 nodes. The input data for each node includes its ID, elevation, base demand, and number of connected pipes. By dividing the input flowrate to AL-Saray water network by the total number of nodes, the base demand of each node was determined.

This analysis took into account the two feed flowrate (FFR) values of the AL-Saray water network, which were 3522 and 5870 m^3/day. These figures were calculated by multiplying the Al-Saray district's population (7500) by the average daily per capita water demand. The base demand from each node was determined to be 20.595 and 34.325 m^3/day for the total feed from Old Kufa WTP values of 4500 and 7500 m^3/hr, respectively, by dividing each of these flowrates by the number of demand nodes (171).

2.3.5 Pipes inputs data

Each of the 265 pipes needs its pipe ID, inner diameter, length, number of nodes at the start and end of the pipe, and Hazen-William roughness coefficient (C) as input data in order to use the EPANET software. The water network in Al-Saray is made up of 270 pipelines. PVC (C=150) made up some of these pipes, while ductile iron (C=140) made up the rest.

2.3.6 PODDS Parameters input data

In order to apply PODDS Model, the input data for each of the 265 pipes include: the Gradient describing relationship between yield strength and ability of cohesive layer to increase turbidity K (NTUm3N-1),Power term to allow for nonlinear forms describing the relationship between yield strength and ability of cohesive layer to increase turbidity b , Power term to relate the release of material to the excess shear stress n , Coefficient of eroding force P (NTUm3N-1s-1) and Maximum turbidity (discoloration) potential Cmax (NTUm). The PODDS Parameters input for these pipes are presented in Table 1.

Table 1: The PODDS Parameters

Pipe material	Inner Diameter	Cmax	K	n	b	P
PVC	213	100	-3	1	1	0.0004
ductile iron pipes	100	100	-0.5	2.5	1	0.002

The Predictive Modelling the turbidity response in Al-Saray water network will be presented for ductile iron pipe No.18 with diameter 100 mm and 100.31m length and PVC pipes Nos. 1,14,15 and 16 with diameter 213 mm and 531.40,38.59,45.50 and 40.37 m length, respectively. Selected in same paths in the network considering feed flowrate (FFR) of 3522 and 5870 m^3/day that gives a base demand value of 20.595 and 34.325 m^3/day respectively. for each node. Fig. 6 shows the locations of the Three selected pipes.

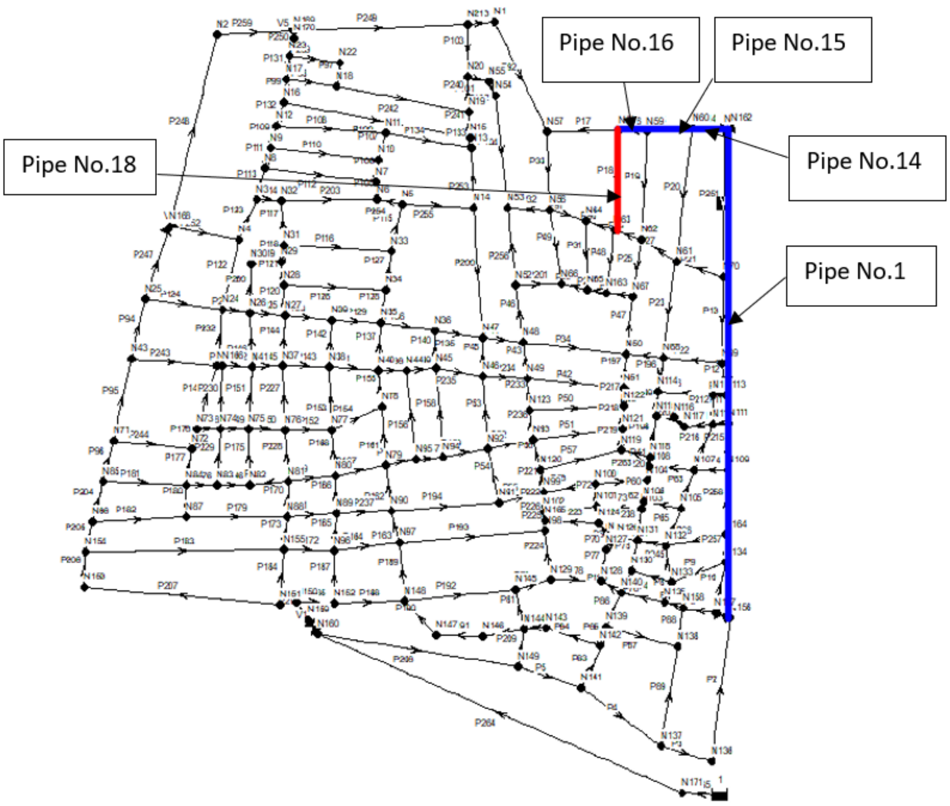


Fig. 6: Location of selected Pipes in Al-Saray water network.

3 Results and Discussions

The results will be presented for the selected pipes in the network considering Feed water turbidity (Source quality) is zero and two cases for feed flowrate (FFR). Case-1: during this case, it was assumed that Al-Saray water network is fed with 3522 m^3/day. Case-2: during: during this case, it was assumed that Al-Saray water network is fed with feed flowrate of 5870 m^3/day.

Case-1: Feed flowrate of 3522 m^3/day

The temporal change of flow velocity in pipe Nos. 1, 14, 15, 16, and 18, respectively, is shown in Fig. 7. The Al-Saray water network's flow velocity is shown to vary with time in Fig. 7, with each pipe experiencing this variation at a different value but with the same general trend. As seen in Fig. 5, the temporal variation corresponds to the demand pattern. The statistics show that flow velocity increases during periods of high-water demand and decreases during periods of low water demand. The values of the flow velocity in this pipe ranged from 0.009 to 0.209 m/sec.

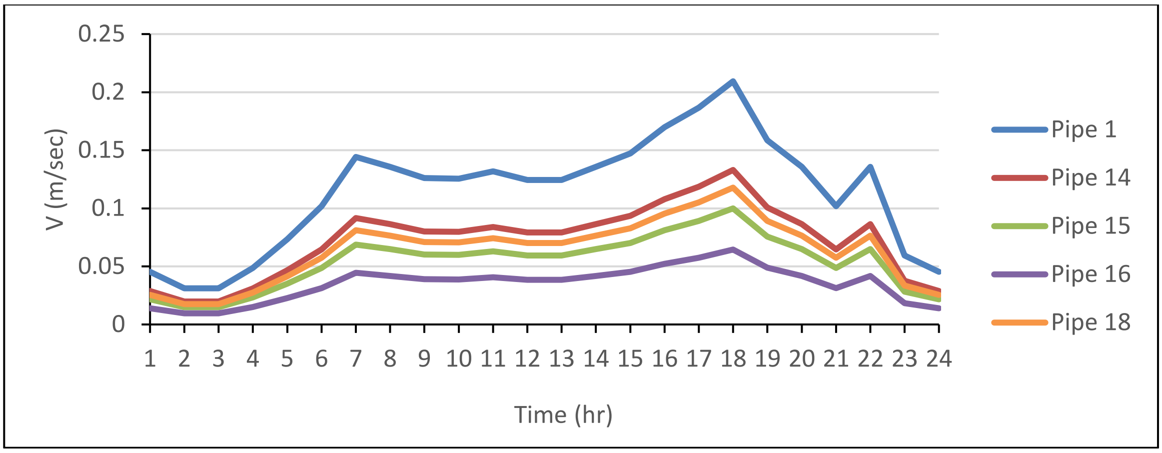


Fig. 7: Temporal variation of flow velocity in pipe Nos. 1,14,15,16 and 18: FFR=3522 m³/day

The temporal change of flowrate in pipe Nos. 1, 14, 15, 16, and 18, respectively, is shown in Fig. 8. the flow rate fluctuates in each pipe in accordance to the demand pattern presented in Fig. 5. The values of flowrate in this pipe ranged from 11.89 to 644.85m³/day.

Fig. 9 shows the predictive turbidity response for pipes Nos. 1, 14, 15, 16, and 18. This graphic makes it evident that the flow rate affects the turbidity levels in the pipes. There were periods of increased water demand when there were high turbidity values. Additionally, pipe Nos. 1, 14, 15, 16, and 18 had maximum turbidity values of (4.55, 3.34, 2.05, 3.02, and 4.02) NTU, respectively.

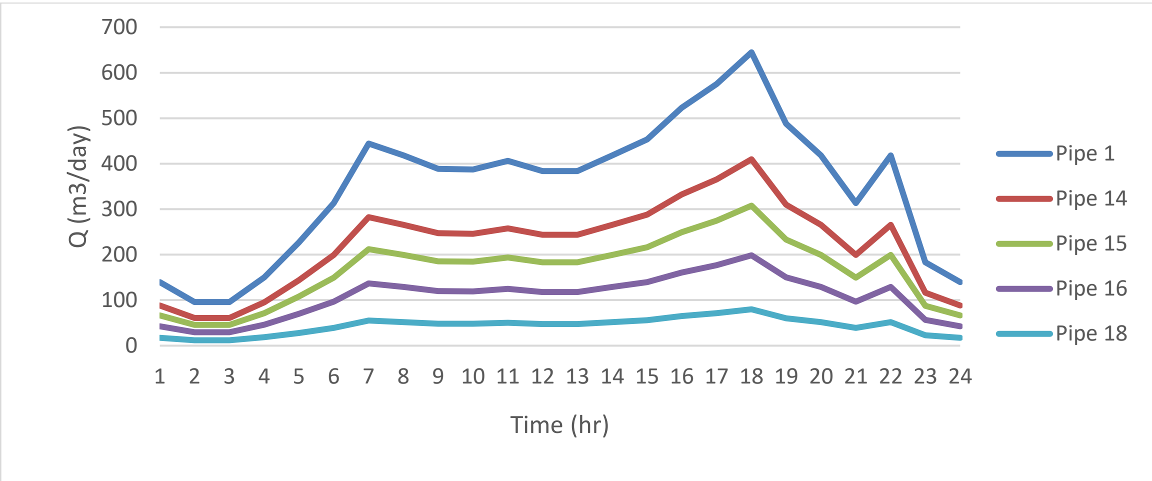


Fig. 8: Temporal variation of flowrate in pipe Nos. 1,14,15,16 and 18: FFR=3522 m³/day

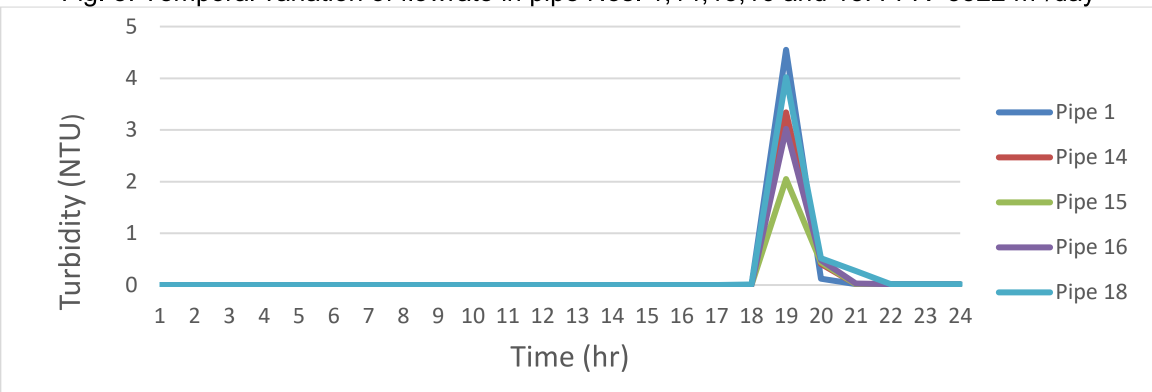


Fig. 9: The predictive turbidity response in pipe Nos. 1,14,15,16 and 18: FFR=3522 m³/day

Case-2: Feed flowrate of 5870 m^3/day

The flow velocity temporal variation in pipes Nos. 1, 14, 15, 16, and 18 is depicted in Fig. 10. Each pipe's flow velocity varies, just like in (case-1), in line with the demand pattern shown in Fig. 4. The flow rates in these pipes varied from 0.02 to 0.35 m/sec.

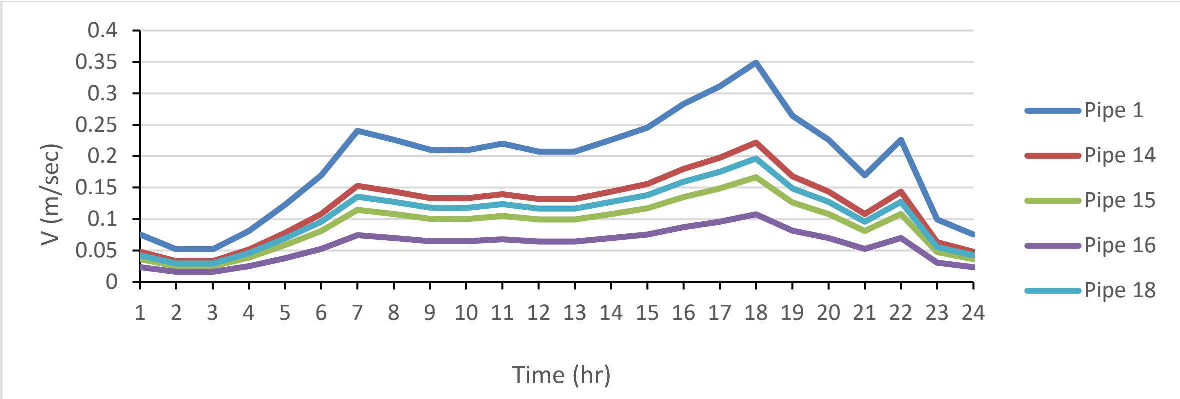


Fig. 10: Temporal variation of flow velocity in pipe Nos. 1,14,15,16 and 18: FFR=5870 m3/day

The temporal change of flowrate in pipe Nos. 1, 14, 15, 16, and 18, respectively, is shown in Fig. 11. The values of flowrate in this path ranged from 159.76 to 1074.74 m^3/day.

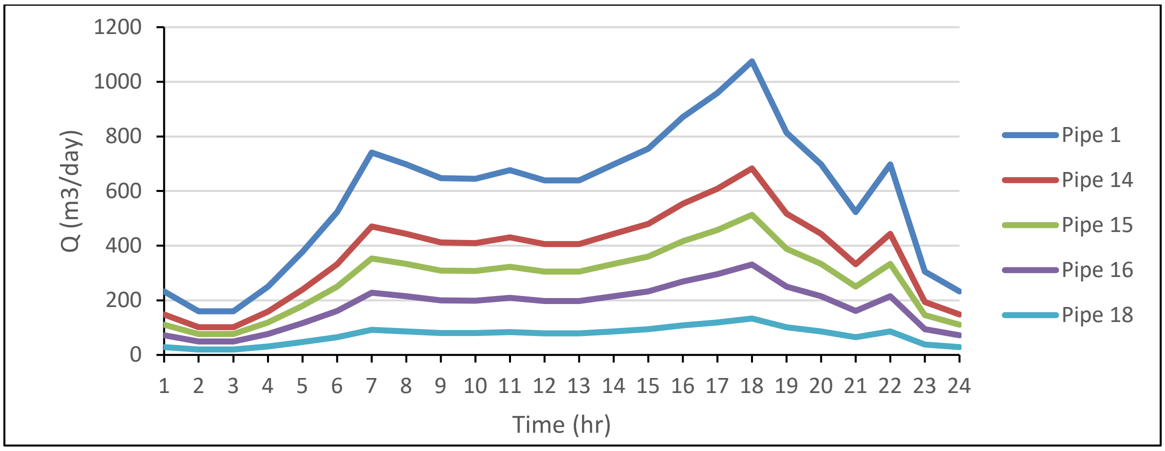


Figure (11) Temporal variation of flowrate in pipe Nos. 1,14,15,16 and 18: FFR=5870 m3/day.

In Figure 12, the predicted turbidity response for pipes Nos. 1, 14, 15, 16, and 18 is displayed. The turbidity levels in the pipes vary according on the flow rate, as this figure makes evident. Its value has increased in comparison to the (case-1), and this is because the pipes ‘velocity values have increased along with their corresponding flowrate values. Periods of increased water demand were associated with high turbidity readings. where the maximum turbidity readings in pipe Nos. 1, 14, 15, 16, and 18, which were 6.07, 6.05, 8.26.7.57, and 9.87) NTU, respectively. The turbidity of the water does not meet the Iraqi regulations (5 NTU) [16], despite the feed water's turbidity (source quality) is zero.

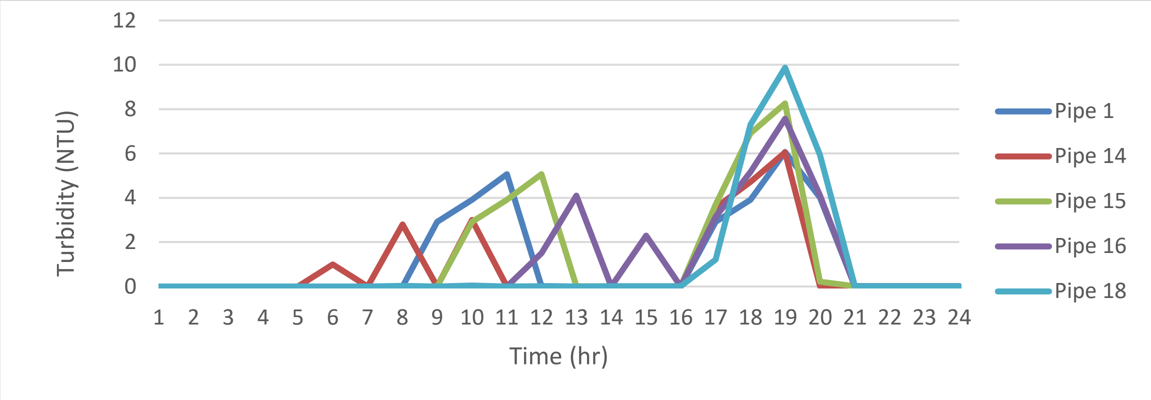


Fig. 12: The predictive turbidity response in pipe Nos. 1,14,15,16 and 18: FFR=5870 m^3/day.

For the cohesive sediment layer to build up at the pipe wall, shear stress caused by the running water must be applied. There is no problem in (case -1) because the material layers are conditioned to daily flow, or shear stress. However, when the flow increases due to an increased demand for water, the fluid's shear stress exceeds the material layers' shear strength, which leads to the material becoming mobilized.

The developed PODDS models can be used to design the hydrants used for mains flushing (cleaning), estimate the turbidity-causing materials in water networks as a result of pipes burst during flushing, and predict turbidity increase as a result of increasing the water demand and subsequently the flow velocity in network mains.

4 Conclusions

Predictive Modeling the turbidity response in AL -Saray water distribution network, using PODDS model led to the following conclusions:

1) The flowrate values in the Al-Saray network varied on the ranges (11.89 to 644.85) and (159.76 to 1074.74) m^3/day, when the values of feed flowrate were 3522 and 5780 m^3/day, respectively.
2) The flow velocity values in the Al-Saray network varied on the ranges (0.009 to 0.209) and (0.02 to 0.35) m/sec, when the values of feed flowrate were 3522 and 5780 m^3/day, respectively.
3) When Al-Saray water network is fed with water at a flowrate of 5780 m3/day, the water turbidity may reach values of (6.07, 6.05, 8.26.7.57, and 9.87) NTU.
4) the material layers are conditioned to daily flow, or shear stress. However, when the flow increases due to an increased demand for water, the fluid's shear stress exceeds the material layers' shear strength, which leads to the material becoming mobilized.
5) The turbidity of the water does not meet the Iraqi regulations (5 NTU), despite the feed water's turbidity (source quality) is zero.
6) The developed PODDS models can be used to predict turbidity increase as a result of increasing the water demand and subsequently the flow velocity in network mains.

References

[1] WORLD HEALTH ORGANIZATION.: Guidelines for drinking-water quality: second addendum. Vol. 1, Recommendations. World Health Organization, 2008.
[2] HOSSAIN, A.: CFD investigation for turbidity spikes in drinking water distribution networks, Doctoral dissertation, Swinburne University of Technology, Faculty of Engineering and Industrial Sciences, 2005.
[3] HUSBAND, P. S. – BOXALL, J. B.: Asset deterioration and discolouration in water distribution systems, Water Research, Vol. 45, Iss. 1, 2011, pp. 113-124.
[4] BOXALL, J. B. –SKIPWORTH, P. J. – SAUL, A. J.: A novel approach to modelling sediment movement in distribution mains based on particle characteristics. Water Software Systems, vol.1, 2001, pp. 263–273.

[5] BOXALL, J. B. – SAUL, A. J.: Modeling discoloration in potable water distribution systems. Journal of Environmental Engineering, Vol. 131,Iss. 5, 2005, pp.716-725.

[6] BOXALL, J.B. – PRINCE, R.: Modelling discolouration in a Melbourne (Australia) potable water distribution system, Journal of Water Supply: Research and Technology, Vol. 55, Iss. 3, 2006, pp. 207–219.

[7] HUSBAND, P. S. – BOXALL, J. B. – SAUL A. J.: Laboratory studies investigating the processes leading to discolouration in water distribution networks, Journal of Water Research, Vol. 42, 2008, pp. 4309–4318.

[8] RYAN, G. – MATHES, P. – HAYLOCK, G. – JAYARATNE, A. – WU, J. – NOUI-MEHIDI, N. – GRAINGER, C. – NGUYEN, B. V.: Particles in water distribution systems, Cooperative Research Centre for Water Quality and Treatment, Salisbury, Australia. Research report 33, 2008.

[9] HUSBAND, S. – BOXALL, J. B.: Field studies of discoloration in water distribution systems: model verification and practical implications". Journal of Environmental Engineering, Vol. 136, Iss. 1, 2010, pp. 86-94.

[10] VAN THIENEN, P. – VREEBURG, J. H. G. – BLOKKER, E. J. M.: Radial transport processes as a precursor to particle deposition in drinking water distribution systems, Water research, Vol. 45, Iss. 4, 2011, pp. 1807-1817.

[11] HUSBAND, S. – JACKSON, M. – BOXALL, J.: Identifying material accumulation processes in drinking water distribution systems with extended period EPANET MSX turbidity simulations. Procedia Engineering, Vol. 119, 2015, pp. 398-406.

[12] SUNNY, I. – HUSBAND, S. – BOXALL, J.: Simulating long term discolouration behaviour in large diameter trunk mains". Environmental Science: Water Research & Technology, Vol. 9, Iss. 3, 2023, pp. 756-771.

[13] ABED, Z. H. – KHUDAIR, K. M.: MODELING OF TURBIDITY DISTRIBUTION IN WATER NETWORKS USING PMS MODEL - AL-SARAY SECTOR IN KUFA CITY AS A CASE STUDY. Kufa Journal of Engineering, vol. 14, Iss. 3, 2023, pp. 48-68, doi:10.30572/2018/KJE/140304.

[14] ROSSMAN, L.A.: EPANET 2.0 User Manual. Water Supply and Water Resources Division, National Risk management Laboratory, USEPA, Cincinnati, OH., 2000, pp. 1-200.

[15] STEEL, E. W. – MCGHEE, T. J.: Water supply and sewerage, McGraw Hill Book Company, New York, 5 th edition, 1960.

[16] WORLD HEALTH ORGANIZATION.: A compendium of drinking water quality standards in the Eastern Mediterranean Region. 2006, pp. 1-44.