# A GIS-based water distribution model for Zhengzhou city, China

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## ABSTRACT

Many water companies in China are developing GIS as a computer-based tool, for mapping and analyzing objects and events that happen on a water distribution network. However, only a few companies have taken a further step to develop a hydraulic model based on GIS, and Zhengzhou Water Supply Corporation is one of them. The WaterGEMS V8 XM from Bentley is used to develop the hydraulic model for the water distribution network in Zhengzhou city, which has a population of over 3 million. During establishment of the model, some of the data extracted from GIS are missing, abnormal, and redundant and require careful screening, searching, and judging. Model calibration is performed after a sensitivity analysis. Peaking factor and pipe roughness coefficient are key model parameters to calibrate. In calibrating peaking factors, the distribution system is divided into 5 operation districts with different types of water usage. To calibrate pipe roughness coefficients, the system was divided into 4 water supply districts with different attributes of pipelines. Finally, a case study of pipe layout evaluation it shows the hydraulic model to be a powerful tool for water supply management.


**Key words** | GIS, hydraulic model, model calibration, water distribution network

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## INTRODUCTION

Water companies in China are facing a challenge of limited water supplies against the needs of the world's largest population, and demands for rapid economic growth. The most effective way to deal with the challenge is to improve water supply management. Many water companies in China are developing GIS as a tool to handle various complex problems of pipelines. However, GIS is just a computer-based mapping tool that can not resolve the problems by itself. For essential tasks such as new development, rehabilitation planning, daily operation, emergency response and water quality investigation, etc., a hydraulic model is required to facilitate these tasks. Zhengzhou Water Supply Corporation is one of the pioneers in China to apply the hydraulic model in water supply management.

Zhengzhou city is the capital of Henan province in central China, as shown in Figure 1. There is only one water company, state-owned Zhengzhou Water Supply Corporation, in the city. Table 1 lists the major data for the water distribution network managed by the company. The water sources are surface water from the Yellow River and groundwater. The earliest pipelines were installed in the 1950s, and most of the pipelines were installed after the economic reform of China, in 1978. The network is facing problems of pipe burst, water leakage and low pressure. Since the cost of rehabilitation and replacement of pipelines is very high, a hydraulic model is desired to generate a cost effective plan for pipe replacement and implement network vulnerability analyses. Furthermore, the model is also expected to analyze proper response to emergency situations, balance the use of multiple water sources, estimate the cost of rehabilitation, and generate appropriate solutions to solve various problems of the network. To fulfil these requirements, a hydraulic model for water distribution network analyses is thus established in this study.

Most of the data required to establish the hydraulic model are extracted from GIS. A model must be calibrated before it can be used. To effectively implement the calibration, a sensitivity analysis is performed to establish key parameters. In

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**Figure 1** | Zhengzhou city.

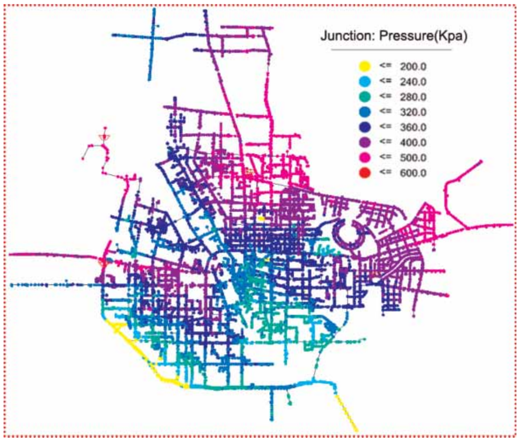


**Figure 2** | Zhengzhou water distribution system pressure.

**Table 1** | Water supply in Zhengzhou city (2008)

| | |
|---|---|
| Area coverage | 339 $km^2$ |
| Population served | 3.265 million |
| Capacity of water supply | 1,070,000 CMD |
| Maximum daily supply | 790,000 CMD |
| Average daily demand | 650,000 CMD |
| Total length of the pipe up to service pipe | 2,200 km |
| Maximum diameter of the pipe | 1,200 mm |
| Average daily operating pressure | 0.32 MPa |
| Non-revenue water | 21% |

order to calibrate peaking factors and pipe roughness coefficients, the network was divided into 5 operation districts and 4 water supply districts, respectively. The calibrated model was then used to evaluate pipe layout alternatives for the construction of a subway station in Zhengzhou city (Figure 2).

## LITERATURE REVIEW

Network model calibration should always be performed before any network analysis activity. Walski (1990) demonstrated that the best tools for model calibration are a lot of detective work, a little intuition and just a pinch of luck. Lansey & Basnet (1991) developed rigorous, non-linear programming algorithms, which incorporate a network simulation model in order to solve the long, tedious calibration problem. Ormsbee *et al.* considered the explicit (Ormsbee & Wood 1986) and implicit (Ormsbee 1989) calibration approaches, and proposed a seven step methodology (Ormsbee & Lingireddy 1997) for network model calibration as follows: (1) identify the intended use of the model; (2) determine initial estimates of the model parameters; (3) collect calibration data; (4) evaluate the model results; (5) perform the macro level calibration; (6) perform the sensitivity analysis; and (7) perform the micro level calibration. Meier & Barkdoll (2000) described the use of a genetic algorithm to optimize the sampling design. Goktas & Aksoy (2007) developed the QUAL2E model linked with a genetic algorithm in order to conduct the calibration and verification of the water quality model. Kumar *et al.* (2008) proposed a state estimation method using graph-theoretic concepts to reduce the dimensionality of calibration problem. Takahashi *et al.* (2010) presented a calibration methodology to address uncertainty environments, such as poor information management, high leakage and the presence of a large number of illegal connections, allowing the calibration of pipe diameter, roughness, minor losses, nodal demands and leakages. It is necessary to introduce some practical experiences and procedures, which would probably be recommended from recent model calibration work done at the Zhengzhou utility.

## THE HYDRAULIC MODEL

The WaterGEMS V8 XM from Bentley has been used to develop the hydraulic model. The distribution network includes 44,150 pipes, and 43,550 nodes. Reservoir, junction, pipe and valve are major elements in modeling the network. There are 4 water treatment plants that are regarded as reservoirs in the simulation. All customers, including water leakage, are junction nodes in the system.

After the elements and network topology are defined, the state of the system is simulated by a steady state analysis, for which the hydraulic demands and boundary conditions do not change with respect of time. The output flow rates of 4 water treatment plants are also simulated. The model was calibrated with data on 2009/6/15, when the water demand was at the peak of the year, and the total maximum demand was 10714 L/s.

## PROCEDURE OF CREATING AND CALIBRATING THE HYDRAULIC MODEL

The key steps in the procedure of model creation and calibration in this study follow below.

### Data collection

The data collected to develop the model are listed in Table 2. For pipe diameter over 200 mm, the WaterGEMS V8 XM extracted the required data from GIS automatically. However, the pipeline diameters of critical customers are always below 200 mm. In order to link these critical customers to the network, we collected and input the pipeline data manually.

There is no attribute for pipeline elevation in GIS. The whole Zhengzhou city is thus divided into 850 sub-areas to determine the elevation of each sub-area according to GIS mapping.

**Table 2** | Data for model creation

| Source | Attribute |
|---|---|
| GIS (pipeline) | Length, diameter, material, date in service |
| GIS (node) | Location, elevation |
| Customer record | Consumption category, consumption pattern, water demand |
| Pressure measurement | Hydraulic gradient of node |
| SCADA | Hydraulic gradient of node, flow rate at reservoir node |

Some data provided by GIS are missing, abnormal or redundant. They need careful screening, searching and judging to resolve these problems. By doing this, we not only make use of data from GIS, but also double check the correctness of these data.

### Initial demand of node

The model has been calculated with data from 2009/6/15, when the water demand was at the peak of the year. Average daily demand was estimated from average monthly customer demand. According to the water consumption pattern of a customer, the peaking factor (PF), as the equation shows below, is defined as the ratio of maximum daily demand and average daily demand. The maximum daily demands of all nodes are then determined, as listed in Table 3, and used as the initial customer demands of nodes for executing the model.

$$\mathrm{PF} = Q_{\max}/Q_{\mathrm{avg}}$$

where PF = peaking factor; $Q_{\max}$ = maximum daily demands (L/s); and $Q_{\mathrm{avg}}$ = average daily demands (L/s).

The PF values are 1.4, according to the variation of total demands on 2009/6/15.

**Table 3** | Initial demand and PF

| Customer category | Demand (L/s) | Initial PF | Typical locations in the network |
|---|---|---|---|
| *Total demand 10,714 L/s* | | | |
| Critical customer[a] | 3,336 | 1.4 | Demands of 29 customers are obtained from SCADA, the others are estimated |
| Household | 1,582 | 1.4 | Line endpoints of 5 districts |
| Group[b] | 3,011 | 1.4 | Endpoints of 35 metered districts, excluding critical customers and line endpoints |
| Leakage[c] | 2,785 | | All nodes according to the equivalent length method |

[a]The total demand for 1,031 critical customers is more than 31% of the total demand for the system.
[b]A group of water consumers who share the same water meter.
[c]The leakage is 26% of the total system demand.

## Sensitivity analysis

There are more than 40,000 nodes in the hydraulic model. In order to effectively implement model calibration, a sensitivity analysis of all nodes was performed.

If we increase the value of a parameter by a percentage, the node demand and pipe roughness coefficient will change. After parameter values are changed, the pressure of each junction node together with the water supply of each reservoir node will be changed at the same time, noted as $\Delta H$ and $\Delta Q$. All these changes are factors in measuring the sensitivity of a parameter:

$$X = \frac{K_1}{n}\sum_{i=1}^{n}\left(\frac{|\Delta H_i|}{H_i}\right) + \frac{K_2}{m}\sum_{j=1}^{m}\left(\frac{|\Delta Q_j|}{Q_j}\right)$$

where $X$ = sensitivity; $K_1$ = weight for a junction node; $K_2$ = weight for a reservoir node; $\Delta H_i$ = pressure difference of junction node $i$ (kPa); $H_i$ = original pressure at junction node $i$ (kPa); $\Delta Q_j$ = supply difference of reservoir node $j$ (L/s); $Q_j$ = original supply at reservoir node $j$ (L/s); $n$ = number of junction nodes; and $m$ = number of reservoir nodes. The sensitivities of some adjustable parameters are shown in Table 4.

## Model calibration

According to the result of sensitivity analysis, the following procedure is implemented to calibrate the model:

(1) adjusting the PF values of critical customers;
(2) calibrating the pipe roughness coefficient; and
(3) fine-tuning the PF and pipe roughness coefficient.

**Table 4** | Sensitivity of parameter

| Parameter | | Sensitivity (%) |
|---|---|---|
| *Junction node* | | |
| Critical customer | Demand | 6.02 |
| | Peaking factor | 18.99 |
| Household | Demand | 1.56 |
| Group | Demand | 3.39 |
| Leakage | Demand | 4.42 |
| Pipe roughness coefficient | | 21.03 |

To adjust the PF values more precisely, critical customers are categorized into 7 types of demand for each one of 5 operation districts, as listed in Table 5. In calibrating the pipe roughness coefficients, we also categorized pipelines in 4 water supply districts (see Table 6 for an example).

## Model performance

After model calibration, we compared the measured and simulated water supplies of reservoir nodes, as listed in Table 7, and Hydraulic Gradient Line (HGL) of 28 checking

**Table 5** | PF value of critical customer in Zhongyuan operation district

| Type of demand | Peaking factor (PF) Initial | Final |
|---|---|---|
| Services | 1.4 | 1.13 |
| High-tech industry | | 1.50 |
| Industry | | 0.86 |
| Domestic | | 2.15 |
| Multi-type | | 0.63 |
| Special industry | | 0.69 |
| Administration | | 1.04 |

**Table 6** | The roughness coefficient C of ductile-iron pipe (DIP) in water supply district No.1

| Initial C value | Average deviation | Diameter (mm) | Number of pipes | Years of service | Final C value |
|---|---|---|---|---|---|
| 120 | −15 | 150 | 2 | 4–9 | 105 |
| | | 200 | 234 | 2–10 | 100 |
| | | 300 | 208 | 2–9 | 105 |
| | | 400 | 75 | 3–8 | 105 |
| | | 500 | 67 | 5–14 | 100 |
| | | 600 | 39 | 4–11 | 100 |
| | | 800 | 8 | 6 | 115 |
| | | 1,200 | 5 | 12 | 115 |

**Table 7** | Comparison of network reservoir nodes after model calibration

| Treatment plant | Measured supply (L/s) | Simulated supply (L/s) | Relative error (%) |
|---|---|---|---|
| Shiyuan | 3,759 | 3,992 | 6.20% |
| Shifo | 907 | 948 | 4.52% |
| Baimiao | 4,442 | 4,112 | 7.43% |
| Dongzhou | 1,606 | 1,662 | 3.49% |

points in the network, as listed in Table 8. From the results of these two tables, the model is ready for other network analyses.

### Model justified

The model was justified with data on 2009/9/18, when the water demand was at the average of the day, and the total demand was 6,835 L/s. We compared the measured and simulated water supplies of reservoir nodes, as listed in Table 9, and Hydraulic Gradient Line (HGL) of 28 checking points in the network, as listed in Table 10. The results show that the average pressure error of all nodes is 1.43 m, and the relative error of the outlet flow rates of water treatment plants is under 10%.

**Table 8** | Evaluation of simulated results against measured values after model calibration

| | |
|---|---|
| Maximum error (m) | 4.44 |
| Minimum error (m) | 0.10 |
| Average (m) | 1.45 |
| Standard deviation | 0.43 |
| Mean percentage error (%) | −0.05 |
| Mean absolute percentage error (%) | 1.07 |

**Table 9** | Comparison of network reservoir nodes after model validation

| Treatment plant | Measured supply (L/s) | Simulated supply (L/s) | Relative error (%) |
|---|---|---|---|
| Shiyuan | 3,152 | 3,004 | 4.68% |
| Shifo | 622 | 674 | 8.39% |
| Baimiao | 2,027 | 2,201 | 8.59% |
| Dongzhou | 1,034 | 956 | 7.54% |

**Table 10** | Evaluation of simulated results against measured values after model validation

| | |
|---|---|
| Maximum error (m) | 4.47 |
| Minimum error (m) | 0.12 |
| Average (m) | 1.43 |
| Standard deviation | 0.38 |
| Mean percentage error (%) | −0.35 |
| Mean absolute percentage error (%) | 1.05 |

## PIPE LAYOUT EVALUATION

Before Qinling Road subway station in Zhengzhou city can be built, two existing pipelines (1,000 mm and 800 mm diameter) near the station must be moved away. A design institute proposed three alternatives for the water company to choose from. The hydraulic model was therefore applied to evaluate these three alternatives, and the pipeline pressure, flow rate, flow direction and velocity were major factors evaluated.

The pipeline pressure is the most important factor concerned. There are 8 SCADA critical points in this area, with 4 additional reference points. At these points, we tried to find out which alternative gives the lowest pressure difference in the network.

Table 11 lists the difference, at SCADA critical points, between the daily operation pressure and the calculated pressure for each alternative plan. From this table, the pressure difference is high (1.88 m) at point No. 5 for Plans A and B, and the pressure differences are under 0.1 for Plan C. Similar situation can be observed from Table 12 for reference points (Figure 3 and 4).

From an economic and engineering point of view, Plan B is better than the others. If the high pressure difference situation at point No. 5 can be improved, Plan B will be the best choice. Therefore, we design an additional pipe to link these two mains, in order to level out the pressure difference. To validate this modified Plan B, we can close some valves to simulate the situation. The measured pressures are coincident with the calculated ones. A comparison

**Table 11** | Pressure difference at SCADA critical point

| SCADA critical point | Pressure difference between daily operation pressure and calculated pressure (m) | | |
|---|---|---|---|
| | Plan A | Plan B | Plan C |
| (1) Heyi | 0.01 | 0.01 | 0.02 |
| (2) Zhengshang Huashan Road | 0.04 | 0.04 | 0.02 |
| (3) Rantun Tongbai Road | 0.04 | 0.03 | 0.03 |
| (4) Zhongyuan Huashan Road | 0.09 | 0.09 | 0 |
| (5) Qinling Gangpo Road | 1.88 | 1.88 | 0.1 |
| (6) Huanghe Restaurant | 0.05 | 0.05 | 0.01 |
| (7) Mianfang West Road | 0.05 | 0.04 | 0.04 |
| (8) Guanwang | 0.03 | 0.03 | 0.03 |

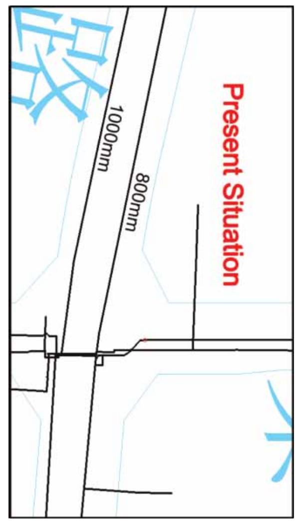


**Figure 3** | Present pipe system for Qinling Road.

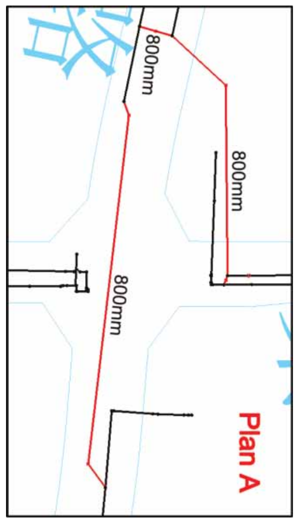


**Figure 4** | Integrated design for Plan A.

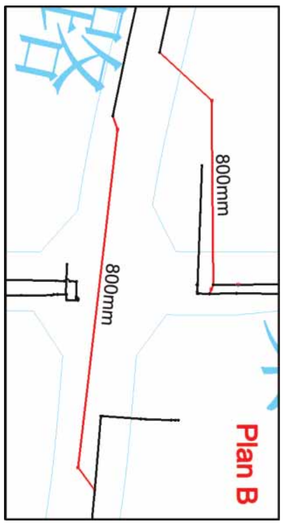


**Figure 5** | Integrated design for Plan B.

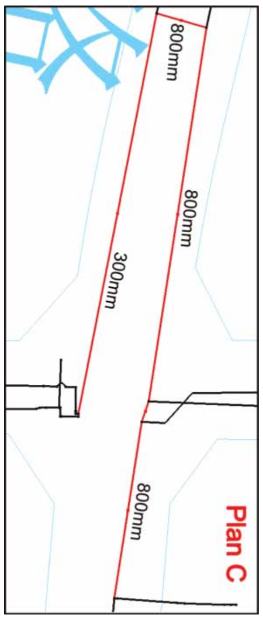


**Figure 6** | Integrated design for Plan C.

**Table 12** | Pressure difference at reference point

| | Plan A | | | | Plan B | | | | Plan C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pressure difference (m)** | **North east** | **North west** | **South east** | **South west** | **North east** | **North west** | **South east** | **South west** | **North east** | **North west** | **South east** | **South west** |
| Maximum | 0.41 | 0.04 | 3.73 | 1.79 | 0.37 | 0.04 | 3.73 | 1.79 | 0.22 | 0.03 | 0.33 | 0.09 |
| Minimum | 0.03 | 0.02 | 0 | 0 | 0.03 | 0.02 | 0 | 0 | 0.02 | 0.02 | 0 | 0 |
| Average | 0.13 | 0.03 | 1.10 | 0.25 | 0.13 | 0.03 | 1.10 | 0.25 | 0.08 | 0.03 | 0.10 | 0.02 |

among hydraulic simulation, site operation results and project cost shows Plan B is better than the others, and it was therefore chosen as the pipe layout for the construction (Figures 5 and 6).

## CONCLUSIONS

(1) To facilitate the intensive work of creating a hydraulic model for a big city, we extracted the necessary data from GIS. For steady state simulation, the average pressure error of all nodes was 1.45 m, and the relative error of the outlet flow rates of water treatment plants was under 10%.

(2) A sensitivity analysis was carried out before model calibration. According to the analysis, peaking factor of critical customer and pipe roughness coefficient are key parameters to calibrate the system.

(3) In model calibration, we categorized critical customers into 7 types of demand for each of 5 operation districts for calbriating peak factors, and categorized pipelines into 4 water supply districts for calibrating pipe roughness coefficients.

(4) By checking the water supplies of reservoir nodes and HGLs of 28 points in the network, the performance of this model is proved to be good.

(5) In a case study of pipe layout evaluation, with the established model, we not only analyze the pipe layout alternatives, but also give a suggestion to level out the pressure difference in a certain layout. Numerous design and operation problems of a distribution network design must be resolved. The hydraulic model can serve as a powerful tool to solve the problems, as the case study demonstrated in this paper.

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