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Identifying Safe Drinking Water Source by Mathematical Modelling for Sustainable Urban Water Supply System

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Abstract: This paper describes the application of mathematical modelling technique for suitable water source identification for its potential utilization in establishing sustainable urban water supply scheme. Rangunia Paurashava of Chittagong district in Bangladesh has been considered for this case study. Water demand for the Paurashava area is estimated up to the year 2040 based on the available population census data. Mathematical models are developed to assess the potentiality of SW and GW sources against the existing and projected water demand. For SW model, the Eastern Hill Region Model (EHRM) developed and maintained by Institute of Water Modelling (IWM), Bangladesh is used for SW source assessment. The flow simulation in the SW model has been carried out by using MIKE-11 software. However, for developing GW model, the hydrogeological setting and aquifer demarcation in the municipality area is established by analyzing the individual lithology and developed hydrostratigraphical sections. In GW modelling, a larger study area has been considered to avoid the boundary influence in model computation and therefore, the developed GW model of the study area spreads over 22 upazillas (sub-districts) of Chittagong, Rangamati and Khagrachhari districts. GW modelling and simulation have been carried out in an integrated MIKE-11 and MIKE-SHE software framework. The simulation results along with measured water quality parameters indicate that none of the SW and GW source is sufficient for sustainable water supply in Rangunia Paurashava even though sufficient quantity of water is available from both sources. However, SW source is highly associated with water quality issues and some of the parameters cross the Bangladesh standard, whereas the GW has the acceptable quality. Therefore, the present study concludes that upon having a suitable treatment of SW, existing SW rivers and GW aquifers can be used as suitable sources of water for sustainable water supply in Rangunia Paurashava of Bangladesh.

1. INTRODUCTION

Identification and establishment of safe and sustainable water source is one of the important component for designing any urban water supply system. Adequate water supply with acceptable quality is the most challenging job to the urban development authorities in developing countries, which is a necessary obligation and important concern for sustainable urban development (Karim and Mohsin, 2009). Therefore, development activities in a country are at present very relevant to its water consumption characteristics. The problem is more serious particularly in the urban segment of a country (Garcia et al., 2008). United Nations predicted that about 56% of the

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people in developing countries would be resided in urban areas in the next decades. Likewise, urban population is increasing rapidly in Bangladesh because of natural urban growth and migration from rural areas (Karim and Mohsin, 2009). According to Bangladesh Bureau of Statistics (BBS) (2005) estimation, the urban population in the country was about 38 million in 2005 and just after 30 years expected to be doubled by 2035. Such growth of urban population will certainly add a remarkable burden on the country's target of providing safe water supply and adequate sanitation facilities. In Bangladesh, municipal water supply systems usually depend upon the conventional sources such as the surface water (SW) and groundwater (GW) systems. However, water quantity and quality limitations of the existing conventional sources often impose economic constraints on the system operation requiring additional treatment costs (Shah and Khan, 2008). Therefore, identification and establishment of safe drinking water source is a major challenging task in Bangladesh. The present study concentrates on the Rangunia Paurashava in Bangladesh and a detailed study has been performed to establish safe water source for establishing water distribution networks by applying the mathematical modeling technique. The Paurashava was established in 2000 and presently, it is classified as a "B-class" Paurashava. Its population has been increasing since its inception. It is situated at 38 km. east from the Chittagong district headquarters, in Rangunia Upazilla of Chittagong District under Chittagong Division. It is comprised of nine wards. Although the relative importance of the municipality has ever been growing as a regional centre of trade and commerce, it has no piped water supply facilities at present. Therefore, the overall objective of this study is the assessment of existing SW and GW sources for identifying the safe water source in regard to establishment of long-term water supply options to the Rangunia Paurashava under Chittagong district in Bangladesh.

2. WATER DEMAND ASSESSMENT

In this study, a widespread water demand assessment is done for the baseline year and is projected up to the design year 2040. The demand assessment technique includes both spatial and non-spatial information. GIS-based map of the study area is the spatial data and non-spatial data input includes the demographic characteristics. GIS maps are prepared based on the topographic survey data conducted by IWM in 2010. However, demographic information is collected from the population census reports of BBS for the years 1981, 1991 and 2001. For the baseline year 2010, demographic data are obtained from the social impact assessment (SIA) survey. The population projection in the Paurashava is then performed and per capita demand for growing cities is assigned to the population according to the land use category in the study area. This process is repeated for every five years from 2010 to 2040 and the findings are presented in Table 1.

Table 1: Projected attributes of Rangunia Paurashava in Bangladesh

Description of attributes	Year						
	2010	2015	2020	2025	2030	2035	2040
Growth rate	2.13	2.20	2.26	2.33	2.40	2.48	2.55
Predicted population	36,270	40,432	45,219	51,949	58,497	68,035	77,166
Water demand (m^3/d)	829	1,208	1,725	2,727	4,078	6,117	8,791
Water demand & WTP backwash (m^3/d)	874	1277	1,829	2,901	4,352	6,549	9,443

4. ASSESSMENT OF SURFACE WATER SOURCE

4.1 Regional Model Assessment of Surface Water Systems

In Rangunia Paurashava, conventional water source for drinking water supply is either SW rivers or GW aquifers. Perennial rivers, reservoirs, lakes and ponds are used as the SW source, while underground aquifer is used as the GW source. However, both sources have several limitations like water availability, water quality environment, physical locations, hydrogeology, salinity etc. Therefore, many variables are to be verified for the identification of safe drinking water sources. In order to solve this complex problem, mathematical model for both SW and GW are used to meet the present and projected requirement of the safe drinking water supply for Rangunia Paurashava. Assessment of available SW for abstraction for water supply to Rangunia Paurashava has been carried out from potential sources of nearby Karnafuli River. Rangunia Paurashava is situated on the banks of the Karnafuli River in the Eastern Hilly Region (EHR). The Karnafuli River flows from the Lusai hill of Mijoram state in India to the Bay of Bengal. This river is a perennial river. However, tidal effect influences this river but salinity level in the river near Rangunia Paurashava is low due to enough fresh water flows from the uphill. The Eastern Hill Regional Model (EHRM) covers a catchment area of around 18,722 sq. km. spanning between longitudes 91°20' E to 92°43' E and latitudes 20°44' N to 23°44' N. The four river basins: the Karnafuli-Halda-Ichamati River basin, the Sangu River basin, the Matamuhuri River basin, and the Bank Khali River basin cover an area of approximately 8,831 sq. km featuring predominantly hilly terrain and foothills and a long strip of lowland coastal plains along the Bay of Bengal. After being implemented the mathematical model based forecasting in all flood prone areas under the project 'Consolidation and Strengthening of Flood Forecasting and Warning Services' by FFWC, the updating and validation of EHRM had been conducted for hydrological year from 1998-99 to 2004-05. The present study applies the modeling activities carried out in connection with updating and validation of the EHRM for 2005-06 hydrological year and monsoon 2006 period. The overall performance of the EHRM has remained consistently high over the years. A sample plot of calibrated water level at vicinity of Rangunia Paurashava on the Karnafuli River is presented in Fig. 1.

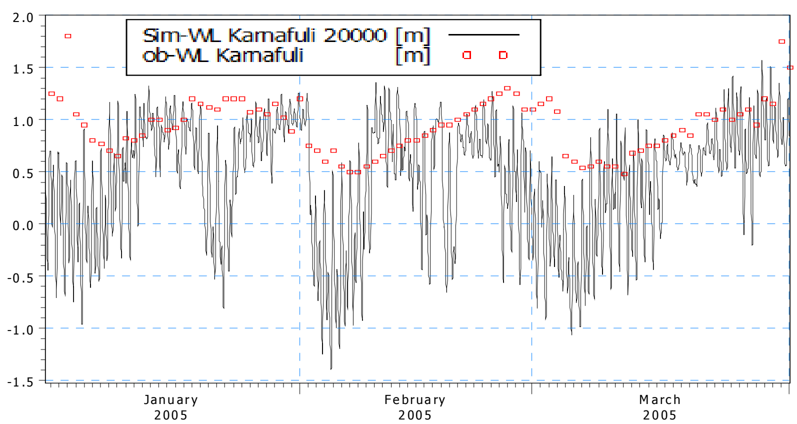

Fig. 1: Calibrated water level at Karnafuli River on the outfall of Ichamati point

4.2 Appraisal of Surface Water Availability

Assessment of SW availability for the water supply in Rangunia Paurashava is carried out from the long-term (comprising of 20-years model run) simulated discharge of validated model available at IWM. The assessment is done in terms of flow duration curve (FDC) prepared from simulated discharge data for year round discharge at the selected location. The discharge at any percentage of probability in FDC represents the flow magnitude in an average year that can be expected to be equalled or exceeded. Dependable flows have been computed for year round analyses for the period of 2004 to 2009 for Rangunia Paurashava and are presented in Table 2. In this study, Weibull method of flow duration curve (Chow et al., 1988) is adopted for dependable flow analysis. This method determines the desired value (i.e. dependable flow) by ranking the daily flows in descending order and assigning each with an exceedence probability. The simple plotting system is expressed by the Weibull plotting position formula as expressed by the Equation (1).

$$P(X \geq x_m) = \frac{m}{n+1} \qquad (1)$$

Where, m stands for the rank number from 1 to n and n is the number of ranked flows. This method has been chosen over several available plotting position formulas in statistics (Chow et al., 1988) because of its simplicity and easy adaptability to computers. The water demand in Rangunia Paurashava along with the requirement of a water treatment plant (WTP) for its backwashing (Table 1) purpose has been estimated as 0.1093 m^3/s (9443 m^3/d) in the year 2040. SW availability from Karnafuli River is found as 1,32,25,248 m^3/d. Moreover, Karnafuli River flows to the southern periphery of the Paurashava, where water is available round the year. From the analysis and findings, it appears that dependable flow in Karnafuli River can meet the water demand of Rangunia Paurashava round the year. Therefore, SW is sufficiently available to fulfill the water demand of the dwellers in Rangunia Paurashava under Chittagong District in Bangladesh and seems to be suitable source for long-term drinking water supply.

Table 2: Dependable flows for the Karnafuli River at Rangunia Paurashava

Location	River	Dependable flow for the dry season (m^3/s)		
		50%	80%	90%
Rangunia	Karnafuli	441.54	255.12	170.13

Required SW withdrawal for water supply to Rangunia Paurashava	= 0.1093 m^3/s
80% dependable flow (from available water) of the Karnafuli River	= 255.12 m^3/s
Available water in the Karnafuli River after withdrawal for water supply	= 255.01 m^3/s
Exploitable flow (60% of 80% dependable flow)	= 153.07 m^3/s
Environmental flow requirement (40% of 80% dependable flow)	= 102.05 m^3/s
Available SW resources for the dwellers in Rangunia Paurashava	= 13225248 m^3/d

4.3 Evaluation of Surface Water Quality

Water quality assessment (Table 3) has been carried out based on the primary water sampling data collection session at the selected locations on the Karnafuli River near Rangunia Paurashava. The first sampling mission was carried out in December 2011 (post-monsoon period) and laboratory testing is performed in DPHE central lab, Dhaka. The test results indicate that only two parameters such as BOD_5 and COD are not within allowable limit. Therefore, water quality results demonstrate that upon reasonable treatment scheme, Karnafuli River water can be taken as a safe drinking water source for municipal water supply in Rangunia Paurashava.

Table 3: Measured surface water quality of the Karnafuli River at Rangunia

Sl.	Parameter	Unit	Bangladesh Standard (ECR, 1997)	Measured Value in Post-Monsoon
1	pH	-	6.5-8.5	8.2
2	BOD_5	mg/L	0.2	2
3	COD	mg/L	4	6
4	Turbidity	NTU	10	0.56
5	NH_3	mg/L	0.5	0.23
6	NH_4	mg/L	0.5	0.24
7	NO_3	mg/L	10	2
9	TDS	mg/L	1000	57
10	TSS	mg/L	10	8
11	PO_4	mg/L	6	<0.98
12	Cr Total	mg/L	0.05	0.002
13	Pb	mg/L	0.05	<0.0035
14	Cl-	mg/L	150-600 (maximum1000)	3

5. ASSESSMENT OF GROUNDWATER SOURCE

5.1 Setting of Hydrogeology and Aquifer System

In this study, GW source assessment is performed based on two major tasks such as hydrogeological studies and GW modeling and simulation. Hydrogeological investigation has been carried out to define the hydrostratigraphic layers in Rangunia Paurashava. Sub-surface lithological characterization and formation of hydrostratigraphic units have been produced by analyzing the individual lithological units and depth of different aquifers from the available five lithological borelogs in the study area. Data analysis suggests that the aquifer is composed of fine sand with some medium sand. The columnar sections produced from borelogs indicate the top most clay layer varying from place to place. Several hydrostratigraphic layers have been identified in the study area and are presented in Table 4. Analysis of aquifer properties indicate that the storage coefficient varies from 0.00112 to 0.00574 with an average value of 0.00379. The transmissivity of the aquifer varies from 303 to 478 m^2/day having a mean value of 377.25 m^2/day. The storage coefficient, columnar section of borelogs and hydrostratigraphic sections indicate that the aquifer is semi confined in nature. By analyzing the stratigraphy of the study area, major hydrostratigraphic units are delineated accordingly and average thickness of individual hydrostratigraphic unit are presented in the Table 4.

Table 4: Summary of hydrostratigraphic units and their extents in Rangunia Paurashava

Hydrostratigraphic Unit	**Depth (m)**		**Thickness (m)**
	From	**To**	
1st Aquiclude	0	08	08
1st Fine sand aquifer	08	30	22
2nd Aquiclude	30	55	25
2nd Fine sand aquifer	55	85	30
3rd Aquiclude	85	100	15
3rd Fine sand aquifer	100	110	10
4th Aquiclude	110	125	15
4th Fine sand aquiclude	125	160	35
5th Aquiclude	160	180	20

5.2 Modeling of Aquifer System

For the purpose of GW source identification and resource assessment, large numbers of hydrogeological and meteorological data have been collected. For hydrogeological study and GW resource assessment, specific emphasis has been given for the municipality area and its vicinity at least the area of Rangunia Paurashava. For the GW modeling, a larger study area is normally considered to avoid the boundary influences in model computations. However, GW model setup involves a geometrical description and specification of physical characteristics of the hydrological system of the area under consideration. In this study, the model has been developed using MIKE-SHE mathematical modeling software tool, developed by DHI Water and Environment Pty Ltd. MIKE-SHE is a comprehensive mathematical modeling system that covers the entire land-based hydrological cycle, simulating surface flow, infiltration, flow through the unsaturated zone (UZ), evapotranspiration and GW flow. It is designed to address dynamic exchange of the water between these components. Major components of the model setup include evapotranspiration, unsaturated zone, saturated zone, overland flow and river systems. The default time step control and computational control parameters for overland flow (OL), UZ and saturated zone (SZ) have been used for entire simulation period. However, simulation periods of the calibration, validation and prediction models were different and user specified. In this study, the model domain covers an area of about 4,574 sq. km., which includes 22 Upazillas of Chittagong, Rangamati and Khagrachhari districts. However, the area of the Paurashava is about 13.34 sq. km. The study area has been discredited into 1000m square grids. The model has 4812 grid cells in each layer, where as 239 grids are the boundary cells and the rest are computational cells. The grid cells are the basic units to provide all the spatial and temporal data as input and to obtain corresponding data as output. The coupling of SW and GW system involves a number of specifications. The river reaches where the coupling will take place have been defined in the river model. In the present study, all the major rivers and khals within the study area have been coupled with GW system. All forms of river-aquifer exchanges and the flooding conditions have also been defined. The flow exchange between the SZ component and the river component is mainly dependent on head difference between river and aquifer and properties of riverbed material such as leakage coefficient. For river-aquifer dynamic flow exchange, leakage coefficients along with the hydraulic conductivity of the SZ are taken into account for most of the river reaches. The developed model is then calibrated for the period of 2000 to 2006. During calibration phase, overland leakage coefficient, vertical hydraulic conductivity, storage coefficient and river leakage coefficient have been adjusted. In the present model, calibration is performed against observed GW level and three observation wells have been used for the calibration and validation purposes. In order to increase the reliability of the model, it is verified based on another set of data, which is taken as 2007 to 2009. After successful calibration and validation of the developed model, it is used for GW simulation and resource assessment purposes.

5.3 Assessment of Groundwater Resource Availability

In this study, GW resource has been estimated based on the well known GW fluctuation technique as well as GW balance study on the basis of long-term simulation. The data analysis suggests that only two geological layers exist within 7m depth. Saturated thicknesses of these two layers have been calculated based on three considerations.

- Case (a): if thickness of first layer exceeds 6m or 7m depth, entire saturated thickness lies only in first layer.
- Case (b): if thickness of first layer remains above GW level, entire saturated thickness lies only in second layer.
- Case (c): if case (a) & case (b) do not occur, then saturated thickness lies in both first and second layers. To find out the thickness of 1st layer within the saturated thickness, simply depth of water table is subtracted from the thickness of 1st layer. Then, part of 1st layer within the saturated thickness is subtracted from the entire saturated thickness to find out the thickness of 2nd layer within the saturated thickness.

According to GW level fluctuation method, saturated thickness of 1st and 2nd layers are multiplied by the corresponding specific yield (S_Y) values and summed up to find out the depth of available water in a model grid. GW storage in volumes is estimated by multiplying the depth of water availability with the area of the grid (volume of water = area x Δh x S_Y, where Δh is the saturated thickness within 6m and 7m depths). Now, total available GW resource is estimated based on the number of grids lying within the area under consideration. Finally, GW resource availability has been assessed in design year 2003 at base condition (selected from return period analysis of rainfall) for two different depths (within 6m and 7m) within Rangunia Paurashava. The result shows that GW resources for under these two different depths are found as 8.06 million cubic meter (MCM) for 6m depth and 9.78 MCM for 7m depth, respectively. In this study, the depth of 6m and 7m is used for the unconfined aquifer to calculate the available GW resources within the limit of suction mode pump. However, in order to maintain the long-term sustainability of the underlying aquifer and sustainable GW resources development in and around the study area, the deeper aquifer has been found more reasonable for water supply. Keeping this in mind, long-term simulation is executed for the developed GW model and a water balance study for the whole model domain has been performed. A trial and error method is applied to find out the maximum abstraction without any negative changes of storage for the deeper aquifer. The net GW recharge for the deeper aquifer is estimated from integrated MIKE-11 and MIKE-SHE simulated output as net recharge = 0 mm (from upper layer) – 6 mm (for outflow) + 619 mm (for inflow) = 613 mm, which mostly comes from the horizontal flow. For this GW recharge amount, corresponding annual aquifer storage volume is estimated by multiplying the aquifer catchment area with the GW recharge and found as 10.57 MCM per annum. For GW quality assessment, a test well has been drilled and constructed screening the target aquifer but water quality test was not performed. Therefore, a survey about GW quality and its acceptance was conducted. It indicates that most (90%) of the respondents replied that GW quality is good enough to be used as drinking water supply. Thus, the aquifer can be used as a potential source of water supply in Rangunia Paurashava in Bangladesh. Nevertheless, it is emphasized that detailed water quality analysis program must be carried out and treatment scheme should be taken prior to consumption.

6. CONCLUSIONS

In this study, an initial attempt has been made for the assessment of conventional water sources such as SW rivers and GW aquifers in order to identify the potential safe water source for sustainable water supply in the Rangunia Paurashava under Chittagong District of Bangladesh. Based on the predicted population and proposed water supply scheme in Rangunia Paurashava, the projected water demand has been estimated as 9443 m^3/d in the design year 2040. The analysis and assessment indicates that both SW and GW sources contain sufficient amount of water resources to meet the demand up to the design year 2040. Moreover, water quality of these two sources is within acceptable limit except very few parameters. Therefore, little treatment scheme is necessary for those few parameters to ensure the high standard. Finally, the study emphasizes and recommends that continuous monitoring of the water quality parameters should be carried out for safe and sustainable supply of water in the Rangunia Paurashava under Chittagong District in Bangladesh.

7. REFERENCES

BBS (Bangladesh Bureau of Statistics), (2005) '*Statistical Yearbook of Bangladesh-2005'*, Bangladesh Bureau of Statistics, Government of Bangladesh (GoB).

Chow, V.T., Maidment, D.R. and Mays, L.W. (1988). *Applied Hydrology*, McGraw-Hill Inc., New York, USA.

ECR (Environmental Conservation Rules) of Bangladesh, (1997) *'Environmental Conservation Rules (ECR) 1997'*, Ministry of Environment and Forest (MoEF), Government of Bangladesh (GoB), Available at: www.moef.gov.bd/html/laws/env_law/178-189.pdf [Accessed on 10 April 2012]

Garcia, A., Sainz, A., Revilla, J.A., Alvarez, C., Juanes, J.A. and Puente, A. (2008) 'Surface water resources assessment in scarcely gauged basins in the north of Spain', *Journal of Hydrology*, Vol. 356(3-4), pp.312-326.

Karim, M.R. and Mohsin, G.M. (2009) 'Assessment of Urban Water Supply Situation: A Case Study in Khulna City Corporation Area', *Proc. of the 2nd International Conference on Water & Flood Management (ICWFM-2009)*, Dhaka, Bangladesh, Vol. 1, pp.235-242.

Shah, M.A.R., and Khan, M.S.A. (2008) 'A Linear Cost Minimization Model for Water Supply Systems with Constrained Sources', *Journal of Civil Engineering (IEB)*, Vol. 36(1), pp.13-22.