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RISK ASSESSMENT OF URBAN DRINKING WATER SUPPLY SYSTEM: A PILOT SCALE STUDY IN CENTRAL INDIA

Pravin Meshram[1], Aabha Sargaonkar[2], Swapnil R. Kamble[3], Shreya Indurkar[3], Vaishali Meshram[4] and Mahendra Thakre[5]

[1]Department of Environmental Science, Sewadal Mahila Mahavidyalaya and Research Academy, Nagpur

[2]CTM Division, CSIR-National Environmental Engineering Research Institute (NEERI), Nehru Marg, Nagpur, India,

[3]Sewadal Mahila Mahavidyalaya and Research Academy, Nagpur

[4]Dept. of Chemistry, Dharampeth M. P. Deo Memorial College, Nagpur

[5]Dept. of Environmental Science, ACS college, Tukum, Chandrapur

Corresponding Email: pravin2668@rediffmail.com, ap_sargaonkar@neeri.res.in, swapnil_rk123@yahoo.in, sheyaindu@gmail.com, Vaishali296@rediffmail.com, mahendra72.thakare@gmail.com

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ABSTRACT:

Hydraulic integrity problems pose high risk of contamination to treated water within the urban water distribution networks. Routine monitoring and end-of-the-pipe water quality testing do not serve the purpose of preventive risk management in this situation. Many times, contaminated water is consumed prior to its assessment, a major concern for public health in developing countries. The paper presents a strategic approach for identification and quantification of risk in a Large-Size Urban Water Supply Systems (LUWSS).

The study uses Geographical Information System (GIS) and Remote Sensing (RS) analysis for mapping, field survey data, and Improved Risk Assessment of Water Distribution System (IRA-WDS) modelling and in-situ measurements of water quality in a pilot study area in Nagpur city. The quantitative risk matrix is generated by quantifying the risk as the product of the probability (likelihood) of occurrence of an event or hazard and the severity of the consequences. Risk characterization from source to consumer indicates High microbial risk due to various activities in the catchment, poor maintenance of the system and intermittent water supply. Model simulations provide exact location of 3% pipes which are in bad condition- that need replacement on priority, and approximately 7% pipes in medium condition - which need regular monitoring and maintenance to ensure drinking water safety. The results are useful to delineate a possible strategy for rehabilitation, and monitoring and maintenance of the network that could be considered to reduce the risks posed by water-quality deteriorating eventsin the distribution systems.

Keywords: - Water Safety Plan, Water Distribution System, GIS, Water Quality, Risk Matrix.

INTRODUCTION :

Safe drinking water supply is very essential for development of society. It is the single most important indicator to determine the public health. In developing countries, purified, disinfected water supply through a piped network is managed centrally by local water supply agencies for urban areas, but rarely made 24/7 (Rosegrant et. al., 2002; Lee & Schwab, 2005; TERI, 2010). Intermittent water supply, high leakage, illegal tapping vis-à-vis. Unaccounted for water (UFW) and unsafe handling are the major causative factors for contamination of treated drinking water. Contaminants that add colour, taste & odour, microbes, heavy metals; as well as toxic compounds such as by-products of chlorination (Trihalomethanes) not only cause the outbreak of waterborne diseases and millions of deaths every year (UNICEF/WHO, 2006) but also Disability-Adjusted Life-Years (DALYs) to many people (WHO, 2008). Reported deaths of children

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less than 5 years of age, due to outbreak of communicable and waterborne disease every year are about 1.6 million (UNICEF/WHO, 2006). It is therefore necessary that Large-Size Urban Water Supply Systems (LUWSS), which generally follow end-of-pipe water quality testing, option for a strategic approach to risk assessment and management. The present study is an attempt in this direction for one of the LUWSS in India.

Water safety plan (WSP) is a proactive approach based on Hazard Assessment & Critical Control Point (HACCP) identification with focus on prevention and control of pollution rather than relying on end product testing (FAP/WHO, 1997). It is an iterative cycle that includes the formation of WSP team, establishment of health-based targets, & assessment of public health concerns vis-à-vis, identification of hazards & vulnerability of the system from catchment to consumer, quantification of risk & suggesting control measures (WHO, 2004). The hazards to water quality are identified by survey, monitoring, & historical records, while the vulnerability is assessed through field studies. The risk due to each of the hazards is quantified as the product of the probability (likehood) of occurrence of the event or hazard and the severity of the consequences due to the venerability of the system (Hokstad et al., 2009).

Success stories of WSP reported in the literature range from small water supply system to large one (Tibatemwa et al., 2004: Mahmud et al., 2007: Sargonkar et al., 2010: Sargaonkar et al.,2013). Rural water supply systems many a times lack water treatment at intake & therefore system assessment mostly relies upon field verification & water analysis. Though rural WSP is similar assessment mostly relies upon field verification & water analysis. Though rural WSP is similar to urban WSP i.e. based on the principle concepts of HACCP, it is made simpler by translating it into public understandable terms for managing the safety of their water supplies more effectively (Mahmud et al., 2007). Successful implementation of WSP for the small water supplies are reported in rural Nepal (Barrington et al., 2013), Tonga (SOPAC, 2007a), Vanuatu (SOPAC, 2007), & Uganda (O'Meally, 2011). Some of the studies may seem identical but each one is unique in terms of its scope, nature of the problem & the way it is addressed at the specific level of simplicity or complexity for local communities.

This paper presents a case study of WSP development for a LUWSS in Nagpur city, India. In addition to routine monitoring of the raw water source, storage reservoir & consumer-end water supply, the study uses RS analysis for catchment assessment & the IRA-WDS modelling to identify the hazards & vulnerable pipes in the network. The decision making study is important in view of the proposed 24/7 water supply for Nagpur city, & also a case example for similar LUWSS in other cities of developing countries.

Water supply system

The extent of water supply system in Nagpur city is from fresh resource- Gorewada Lake through Pench I water treatment plant (WTP), Governor House Master Balancing Reservoir (MBR) up to WDS at the consumer end. Every day, approximately 640 MLD water is distributed to 2.5 million people in ten zones through a 2100 km pipeline. The entire network is managed by the Water Works Division in the city. Due to intermittent water supply (about 1 to 2 hrs/day) in most of the zones, illegal taping & pumping with underground storage in pits is commonly practiced by consumers to fulfil their day-to-day water demand. WSP development is therefore undertaken in one of the sensitive zones in the city for which it is proposed to implement 24/7 water supply. (Fig. 1) depicts the location of Nagpur city, schematics of water supply system

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in the city & a study area in Dhantoli zone considered for WSP development.

The pilot study area within 79°5"15' to 79°6"30'E & 21°7"20' to 21°8"15' N. The water supply network is the pilot study area is approximately 65 km in length, placed 1 to 1.7 m below the ground level. There are 961 household connections & some of the commercial centres & educational institutes also draw water. The sewer network in the study area is approximately 47.21 km in length, placed 1.35 to 1.85 m below the ground & mostly below the distribution network to prevent contamination. The sewer network is 25 to 30 years old & the coverage is partial.

Health-based targets

Development of health-based targets to ensure drinking water safety is the first & important step in WSP. In India, the standards by Bureau of Indian Standards (BIS, 10500:2012) & Central Public Health & Environmental Engineering Organization (CPHEEO, 1999) for urban drinking water supply are well established & therefore same are used as a health-based targets in the present study. This is followed by formation of WSP team. The WSP team includes zonal officers of water works departments, field engineers, plant operators, scientists & professionals from health departments, academic institutions as well as NGOs. The experience & expertise of the team members are used in system assessment & quantification of risk at each stage of water supply.

RS analysis & GIS-mapping

Land use land cover (LU-LC) classification map of Gorewada lake catchment is prepared by supervised classification the multispectral data using ERDAS Imagine 2011 software. IRS-P6 (LISS III) multispectral data (23.5 m spatial resolution) is used in the present study. The LU-LC map is presented in Fig.2.

GIS maps for water supply network, sewer network, open drains, groundwater table, pressure in the pipes, & soil map are presented in Fig. 3 & 4. The corresponding attribute data are presented in Table 1. The spatial mapping takes into consideration the variability in system specific parameters such as pipe material, diameter, length, etc., as well as operational conditions such as leakage, breaks & bursts, water supply duration in the study area. Environmental conditions although remain almost constant for the small pilot area, variability in soil, subsurface characteristics & pollution sources are taken into account.

Semi-quantitative approach

In general, system assessment includes monitoring & sampling at raw water source, water treatment plants, storage reservoirs, WDS network and/or consumer-end water supply. The main purpose is to identify the hazards at each stage of water supply, assess vulnerability of the system & quantify the risk to suggest appropriate control measures. Hazard identification usually relies on survey & seasonal monitoring of water quality or sometimes historical records of repetitive health concern events in the area & complaints received at the water boards. Each of the hazards is assigned a score from 1 to 5 considering its likelihood as once a day, once a week, once a month, once a year or once every 5 years (Deere et al.., 2001). Similarly, vulnerability of the system is assessed considering the factors such as age of the system in place, the material used, readability of the material, operation & maintenance (O&M) of the system & environmental conditions in the study area. As many of these factors are interdepend, difficult to quantify & highly subjective, the present study uses GIS-based Spatial Decision Support System (SDSS) for risk assessment of water distribution network. Vulnerability scores also range from 1 to 5 based on the severity of the consequence or impact as Insignificant, Minor, Moderate, Major, Major or Catastrophic Table 2 (Deere et. al., 2001). To

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assign scores to hazards & the vulnerability of the system at each of water supply, group method of weighting is used in the present study. The experience of WSP team is implemented by forming multiple groups comprising of experts in diverse fields. The overall risk is computed as the product of the probability (likelihood of occurrence of an event or hazard and the severity of the consequences. Approach to quantitative risk assessment is presented in Table 2.

System assessment

Pre-Societal impact zone

The components of water supply system viz. raw water source, treatment plant & storage reservoir are mostly beyond the influence of social activities. In the present study, Gorewada Lake is about 8 km away from urban Nagpur & a well-protected catchment. However, field survey & monitoring indicated certain unauthorized activities in its catchment vis-à-vis cattle grassing, swimming, on-site sanitation & slow encroachment in the nearby areas. The LU-LC classification map shows illegal settlements & open drains. The main hazard to water resource is the domestic waste flowing through open drains. Water monitoring for seasonal change in physcio-chemical & microbial contamination confirmed the hazards.

Pench-I-WTP with installed capacity 136 million litres per day (MLD) comprises of various treatment units pre-chlorination followed by aeration, coagulation, and flocculation. Sedimentation, rapid sand filtration & post chlorination. A few hazards due to operational inadequacies or maintenance of the system are identical during field survey by WSP team. The performance of WTP is evaluated based on the outlet water quality in terms of turbidity, TDS, microbial quality & heavy metals.

Risk assessment

Risk to the raw water source is due to microbial contamination. Major hazards in the catchment of the lakes are domestic waste flowing through open drains & pathogens from faecal animals. The consequences of contamination are known from historical events of outbreaks of waterborne diseases in the city. Considering the health-based targets for coliform bacteria, various groups in WSP team assigned the scores for likelihood & consequences of microbial contamination of the raw water source. In particular, for on-site sanitation activity, the score for likelihood of hazard is once in a day (score 5) by two groups, once in a week (score 4) by two groups, once in a month (score 3) by one group & once in a year (score 2) by one group (Table 2). The average likelihood score estimated by six groups for on-site sanitation activity is 3.8 (Table 3). Similarly, the consequence scores are catastrophic public health impact (score 5) by two groups, major regulatory impact (score 4) by three groups, moderate aesthetic impact (score 3) by one group (Table 2). The average consequences score estimated by six groups for on-site sanitation activity is 4.1 (Table 3).The overall risk score is 15.8. According to the risk classification band, the risk due to on-site sanitation is Very High (Table 3).

Similarly, the WTP and MBR are assessed for physic- chemical as well as microbial risk of contamination. The average scores for likelihood and consequence of hazards to WTP and MBR, and the corresponding risk scores are presented in Table 3.

Societal impact zone

The water supply network in social impact zone mainly comprises of water mains & water distribution network from local Elevated Service Reservoirs (ESRs) to consumer-end. Being underground, system assessment for the entire urban network is a difficult task. Various parameters govern the performance of the system. These include system specific parameters (i.e. pipe length, diameter, material age) environmental factors (i.e. soil in the area

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and ground water table), & operational parameters (i.e. O&M practices which include supply duration, breaks & bursts). Poor maintenance of the system and negligence deteriorate the condition of the WDS. In addition, heavy traffic along the road, poor workmanship makes the system vulnerable to contaminant intrusion. Soil and water pollution, open drains carrying domestic waste are the major hazards for such vulnerable systems and pose high risk of contamination to the treated water supply. Considering all these factors, the present study uses IRA-WDS model for quantification of risk in the pilot study area.

6.2.1 IRA-WDS model

IRS-WDS comprises of three models Pipe Condition Assessment (PCA) model, Contaminant Ingress (CI) model & Risk Assessment (RA) model (Vairavamoorthy et al., 2007)

CI Model

The CIM consists of two parts, the contaminant zone (CZ) model & the contaminant transport (CT) model. The CIM identifies the exact location of the CZ formed in the soil. The CT model simulates the water flux using the Green-Ampt model (Green & Ampt, 1911) and the variable concentration of the contaminant within the CZ assuming as unsaturated flow path for contaminant seepage (Yan et.al., 2002).

PCA Model

The PCA model estimates the relative condition of each pipe in the network using an analytical hierarchical process (AHP) developed by Prof. Saaty (1980). It computes a distance metric for each indicator, viz, pipe age, material, diameter, supply duration, pressure, breaks & bursts, leakage in the system, traffic load & various linguistic parameters. Uncertain human knowledge in linguistic terms about workmanship, bedding conditions & internal & external protection to pipes is described using fuzzy set theory (Zadeh, 1965). PCA uses a multi criteria evaluation (MCE) & fuzzy composite programming (FCP) approach (Bardossy & Duckstein, 1992: Bender & Simonovic, 2000). The defuzzified number is the pipe-condition index, a surrogate parameter that describes the vulnerability of the pipe to the contaminant intrusion (Yan & Vairavamoorthy, 2003).

RA Model

The combination of hazard & vulnerability produces the risk index in the RAM using the weighted linear combination (WLC).

6.2.2. Model parameter estimation

Model parameters are the important inputs in a simulation study. For quantification of risk, records of O&M of the system at the waterworks, pipe breakage frequency & leakage are analysed. According to the annual average pipe breaks & bursts records as 188 in the study area & the expected harm for each pipe as a function of pipe age (installation year), material, diameter & traffic density: the total number of breaks & bursts for each pipe are classified as 2, 4 & 5 per year (Sargoankar & Islam, 2009).

Similarly, considering the records of water loss through leakage & unauthorized consumption, 1,166 litres/day leakage is distributed in the entire network as a function of age (installation year), material (corrosivity) & traffic density. As the old corroded pipe becomes weak due to wall thinning & starts leaking & CI pipes are more vulnerable to external corrosion if left unprotected (USEPA, 2009). Old CI & DI pipes are therefore assigned higher leakage rate in the range 0.0007 to 0.22 litres per second (lps) & GI & MS pipes 0.0009 to 0.08 lps. As traffic is an important parameter to cause damage to the water supply network, linguistic classification as Busy & Medium are considered for traffic density & appropriately used in model parameter estimation.

Model simulation

With complete database of shape files in IRA-WDS model set up (Fig. 3-4) and system

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parameters given in Table 1: CIM provided the possible CZs formed into the soil vis-à-vis hazards for the WDS. PCA model provided the condition of pipes in the network. A linear combination of CI & PCA with relative weights of 0.6 & 0.4 respectively, generated the risk index (RI). The RI indicates the relative risk of contamination intrusion into the pipe network.

RESULTS & DISCUSSION :

RS analysis of Gorewada lake catchment indicates more land cover (grasslands 56 %, forest cover 33 %, water body 8.5%) and less land use (habitation 1.5 % and agriculture 0.9 %) in the catchment area i.e. a well-protected catchment (Fig.2). however, analysis of lake water samples indicates faecal coliform in the range 5 to 60 CFU/100 ml which confirms the contamination of the raw water source by indicatororganisms during monsoon and winter. Thus, the quantification as Very High microbial risk to lake water quality due to various activates in the catchment is considered acceptable. Similar relationships between land use and surface water quality are reported in the literature (TU, 2011). The control measures suggested in this respect to the water works division are presented in Table 3.

For WTP, no major hazards are identified during field survey by WSP team. WTP operates as per Standard Operating Procedure (SOP) and is beyond the influence of any societal activates. Its performance is optimized by continuous online monitoring of pH, residual chlorine, turbidity & conductivity. It is observed that the overall performance of the TP is satisfactory. Routine & random monitoring indicates water quality meets health-based targets in terms of all the parameters. However, a few possible hazards are noted during the survey. Risk quantification & control measures suggested are presented in Table 3.

MBR is one of the most important components in the supply chain. Based on the field verification program, some of the likely hazards are microbial contamination through open lid & poor conditions of the lid. Though the water quality in MBR presently meets the health-based targets, risk classification is extreme risk due to the deteriorated condition of MBR. Therefore, control measures with minor investments & on-site security to protect the MBR from tampering by public are suggested to ensure drinking water safety (Table 3). Similar control measures for some of the other hazards in pre-societal impact zone of water supply system (i.e. for source & treatment plant) are delineated through the experience of the WSP team (Table 3)

For WDS, major hazards are the CZs formed in the soil near open drains & crossings of the water supply lines with leaky sewers. These locations are identified by CIM. The Clay soil in the study area has the large water holding capacity & therefore pipes in CZ are vulnerable to contaminant ingress. As the supply pressure in most of the areas in Medium to Low, risk of contaminating drinking water due to negative pressure in the pipes during non-supply hours is high. Fig. 5 presents the model results for risk mapping of WDS in the study area. PCA statistics indicates that 3% of 1262 i.e. 42 pipes are in Bad condition. Accordingly the relative risk classification 3-4% pipes are in the range of High to Very High. This is confirmed through water quality monitoring program. Water quality analysis at High Risk points indicated FC count 18 to 126 CFU/100 ml verification of the model results (Fig. 5). Thus, application of the IRA-WDS provided exact location of pipes in Bad condition which need to be replaced on priority before implementing 24/7 water supply. About 7% pipes are in medium condition & need regular monitoring & maintenance. Risk quantification due to corroded pipes, illegal tapping & recontamination at the point-of-use are presented in Table 3. The WSP matrix gives details of hazard & vulnerability scores with risk

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characterization at each step of water supply & suggested control measured from catchment of consumer (Table 3).

CONCLUSION :

Development of WSP emphasizes system assessment for each part of the water supply network. In this structured approach, WSP identified the critical points from catchment to consumer, where implementation of control measures is necessary. For Nagpur city, WSP indicated high works department for planning the implementation of control measures with due consideration to financial implications of civil works etc., over a specific period of time.

With the advancement of computer technology & expertise of the staff, application of GIS & mathematical modelling provides a techno-economical methodology for management of the network data, system assessment & decision making. The results of SDSS are certainly useful for managers for rehabilitation of the network & select monitoring at critical locations to reduce the response time to customer complaints. Development & implementation of WSP is a data to decision (D to D) approach that ensures drinking water safety rather than end-of-the pipe testing in LUWSS.

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Table 1: Details of infrastructure and environmental conditions in Pilot area

1. Water Supply

Pipe Material	Installation Year	No of Pipes	Diameter	External Protection	Internal Protection
CI	1980	689	50 to 450 mm	Bad	Bad
CI	2003	405	75 to 150 mm	Bad	Bad
DI	1980	9	225 to 250 mm	Bad	Bad
DI	2003	56	200 to 300 mm	Bad	Bad
MS	1980	34	500 to 700 mm	Good	Good
GI	2003	69	50 mm	Medium	Medium
	Total Pipes	1262	**Bury Depth**	1 to 1.7 m	

2. Sewer Network

Pipe material	Installation year	No of Pipes	Diameter	Bury Depth
RCC	1980	329	50 to 700 mm	1.35 to 1.85 m
SWP	1980	900		
Total Pipes		**1229**		

3	Open Drain	No of Drains	Width	Depth	Length
		3	1.5 to 2.0 m	1.6 to 1.85 m	2.5 to 3.36 km

4	Soil Type	Pore Size Index	Corrosivity	Bulk Density	Soil Porosity
	Clay	0.127	15000	25 g/cc	0.0038 cm/m

5	Groundwater	Category	Ground water table depth	Fluctuation
		Good	3.12 to 10.28 m	0.68 to 1.97

6	Pressure	Category	Medium
		Low	

7	Traffic	Category	Medium
		Busy	

Table 2. Semi-quantitative risk matrix approach (Deere et al. 2001)

		Severity or Consequence				
		Insignificant or no impact- Rating: I	Minor compliance impact - Rating: 2	Moderate aesthetic impact - Rating: 3	Major regulatory impact - Rating: 4	Catastrophic public health impact -Rating: 5
Likelihood of frequency	Once a day- Rating: 5	5	10	15	20	25
	Once a week- Rating: 4	4	8	12	16	20
	Once a month- Rating: 3	3	6	9	12	15
	Once a year- Rating: 4	2	4	6	8	10
	Once every 5 years- Rating: 5	1	2	3	4	5
	Risk Score	<5	>=5	>=10	>=15	>=20
	Risk Band	Low	Medium	High	Very High	Extreme

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Table 3. Hazard scoring and risk characterization for each hazard from source to consumer end and control measures

Stages	Sr. No	Hazardous Event	Basic of Likelihood and consequence score	Hazard	Likeli Hood	Consequence	Risk Score	Risk Band	Control Measures Identified/ Suggested
Catchment of Gorewada Lake	1	Sewage overflow from on-site near catchment sanitation during monsoon	Human settlement near catchment	M	3.5	4.5	15.8	VH	Develop habitation with proper sewer network and collection system
	2	Unauthorized Recreation (swimming, fishing etc.)	Unprotected Catchment	C, M	3.7	4.2	15.5	VH	Prohibit unauthorized access
	3	Pathogens fromferal animals, cattle and birds.	Unprotectedcatchment	M	3.7	4.5	16.7	VH	Provide fencing around the Gorewada catchment
	4	Idol immersion	Religious activities at Temple	C, P, M	2.5	4.2	10.5	H	1. Prohibit religious activities 2. Provide a separate pond for idol immersion
	5	Waste from proposed Zoo project (Future Risk)	Daily visitors at zoo (possible hazard)	C, P, M	3,4	5,0	17	VH	1. Sufficient barrier required recreational area and reservoir 2. Guest houses to be located outside the catchment
WTP (Pench I)	1	Floating particleslike grass andincreasedt urbidity in raw inspection water during monsoon season	Information given by plant operators and Visual	P, M	3.1	3.7	11.5	H	Develop and follow SOP
	2	Mechanical failure	Wear and tear of machinery	C, P, M	3.0	4.5	13.5	H	Ensure proper periodic maintenance
	3	Short circuiting due to excessivehead loss	Information given by Plant Operator	C, P, M	3.2	4.2	13.4	H	Develop and follow SOP
	4	Electric failure	Plant records	C, P	3.0	3.5	10.5	H	Dedicated power line required for WTP
MBR	1	Contamination from vermin, reptiles, birds	Unprotected opening in the roof	M	4.0	3.5	14	H	Installing net. Protect roof
	2	Intrusion of ground water through cracks	Observed by the WSP team during a visit	C	3.7	4.5	16.7	VH	Develop and followSOPs for maintenance

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(Govt. House)		due to tree roots.	to Governor House MBR						ofMBR and good sanitary conditions
	3	Contamination due to deteriorated condition of MBR	Observed by the WSP team during a visit to Governor House MBR	C, P, M	4.7	4.5	21.2	E	Rehabilitate MBR on priority
WDS	1	Corroded pipes	NMC records	C, P, M	2.0	5.0	10	H	Use non-corrosive pipes such as HDPE and MDPE Pipes
	2	Water supply pipes crossing with sewer lines	Customer complaints and visual inspection	P, M	4.0	5.0	20	E	Lay new pipe network as per norms
	3	Pipe bursts	NMC records	C. P. M	2.2	5.0	11	H	1. Laying HDPE and MDPE pipes 2. Provide protection
	4	Bio-film formation	No Residual Chorine	P. M	3.0	4.5	13.5	H	1. Appropriate Chlorination 2. Regular monitoring for Res. CI
	5	Illegal tapings into mains	Potential backflow in supply line	P. M	3.2	5.0	16	VH	1. Provide backflow prevention devices 2. Practice 24/7 water supply
	6	Recontamination at user end	Unsafe handling and storage	M	4.5	4.2	18.9	VH	Public education and awareness programs
Note:		Risk Score:	(>=20)	(>=15)	(>=10)	(>=5)	(<5)		
		Risk Band:	E=Extreme	VH= Very High	H= High	M=Moderate	L= Low		
		Abbreviations:	C = Chemical	P = Physical	M = Microbial				

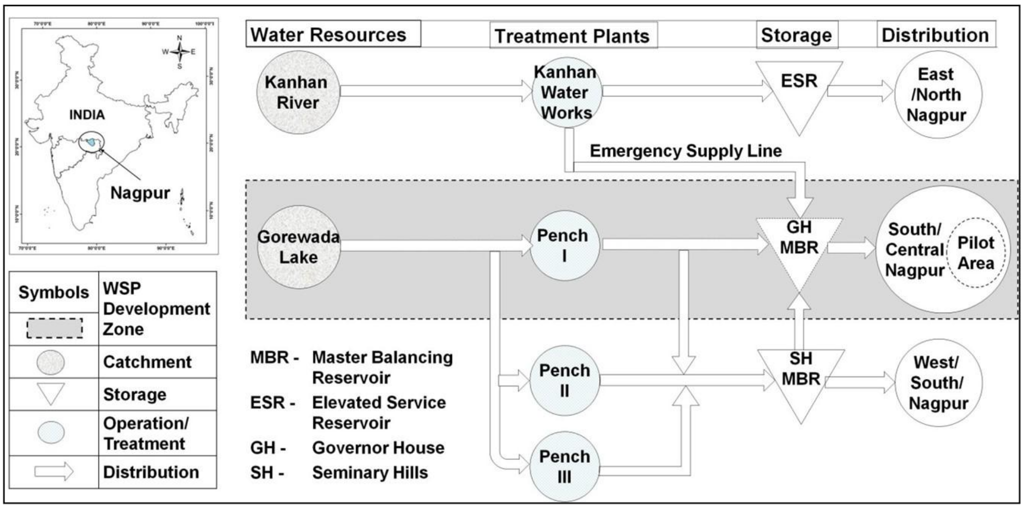

Fig. 1. Components in WSP for Nagpur city, India

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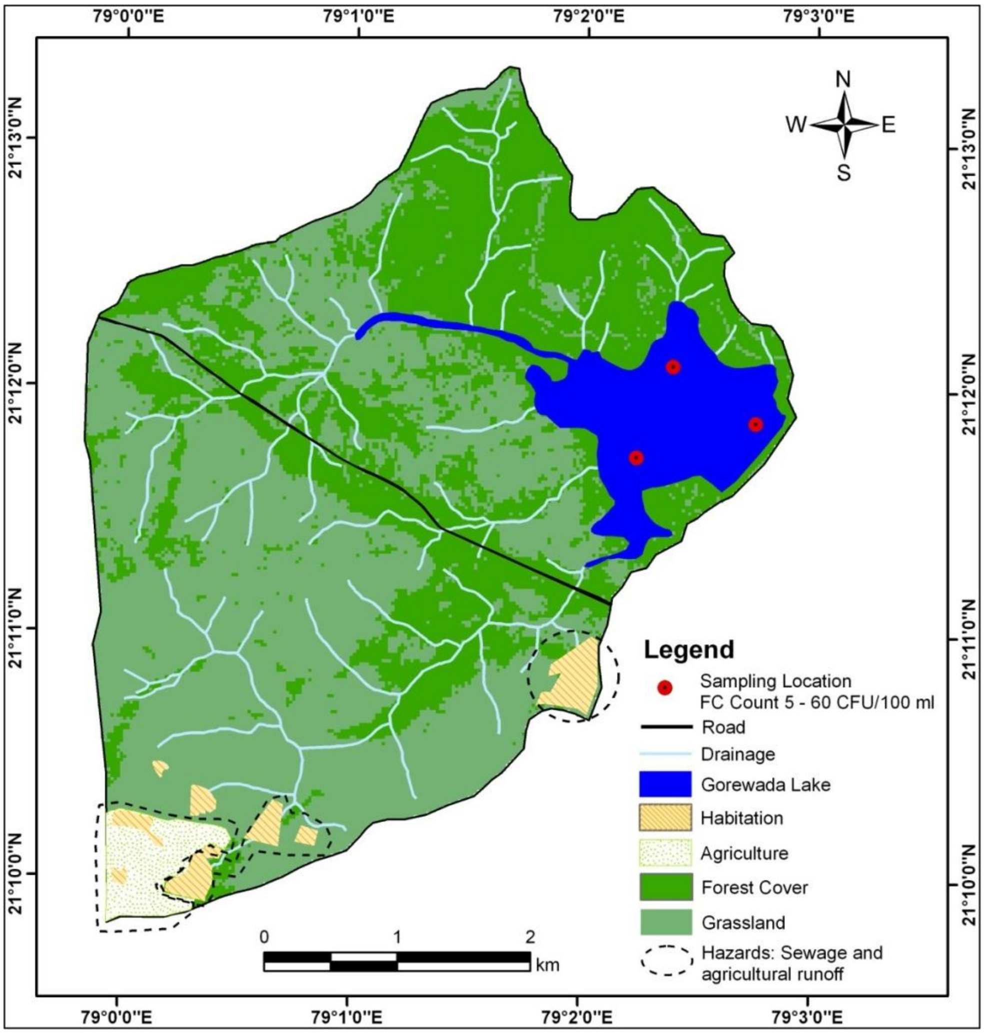

Fig. 2. Land use land cover map of Gorewada Lake catchment

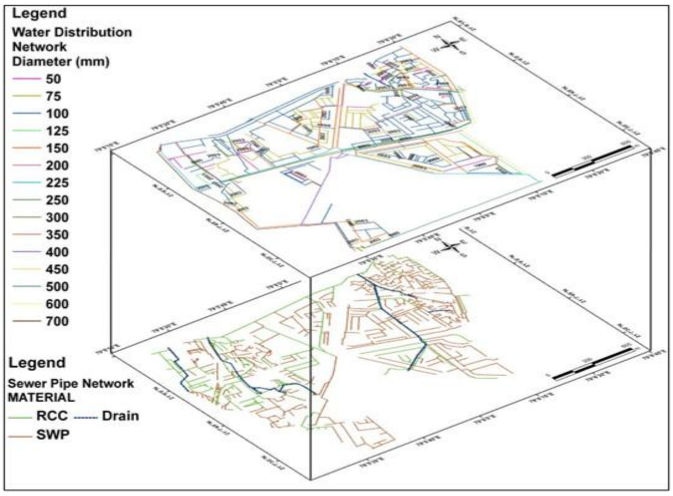

Fig.3. Water supply network and sewer network with open drains in the pilot area

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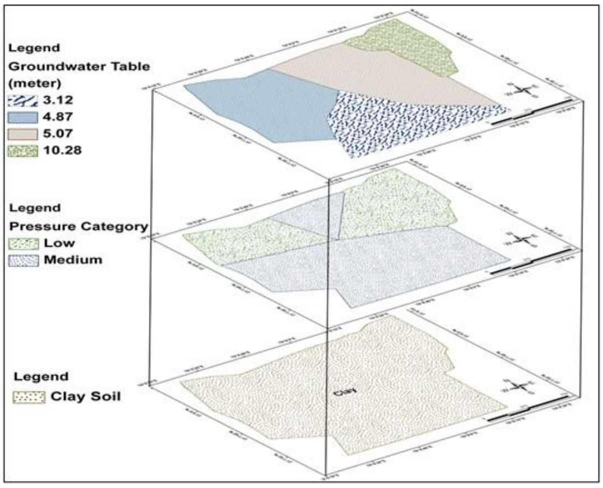

Fig. 4. Average groundwater table, pressure in water supply system and soil type in the pilot area

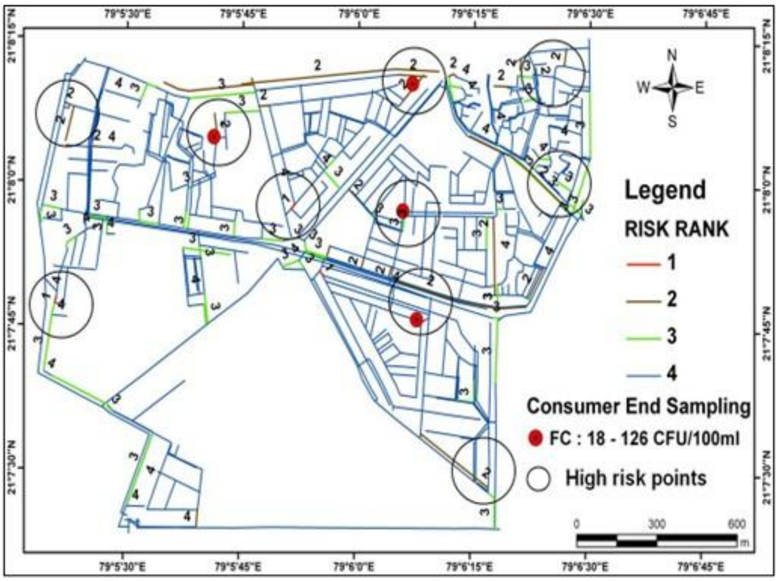

Fig.5. Risk map and verification of high risk points in pilot area

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