Identification and Planning of Water Quality Monitoring Network in Context of Integrated Water Resource Management (IWRM)

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Abstract Hydrological system is a quite complex and dynamic in nature because of the heterogeneity of the earth crust and surrounding atmosphere. Water exists on the earth in all three forms of liquid, solid and gas. The scarcity of its liquid freshwater has resulted because of increasing demand in response to growing population, contamination and pollution of freshwater bodies due to urbanization and industrialization. Precise measurement of water quality, in present time, has become the necessity because of increasing scarcity of this precious resource. In a global perspective, organizations dealing with water supply and monitoring are ever concerned about precise assessment of water quality. Researchers are focusing on the assessment of surface and ground water quality on spatial scale rather than point scale, which needs strengthening of monitoring networks time-to-time. The design of a hydrometric network starts ideally with a minimum number of stations, and increases gradually until an optimum network is attained when the amount and quality of data collected and information processed is economically justifiable and it meets the user's needs to make specific decisions. In hydrology, monitoring of data is mostly site-specific and proper representation of this data on spatial scale requires proper network planning. Since the drivers of water quality vary in space and time, the quality of water also varies in space and time. It is therefore imperative to monitor the quality of water under heterogeneous space-dependent conditions for which a specialized water quality monitoring network is essential. The present paper is in the context of identifying and planning of water quality monitoring network for data acquisition for Integrated Water Resources Management (IWRM).

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Introduction

The monitoring of hydrologic system is known from the ancient times, whereas the first description of the rain gauge and its use is contained in the Arthashastra by Chanakya (300 BC). Varahamihira's (AD 505–587) Brihatsamhita contains descriptions of the rain gauge, wind vane and prediction procedures for rainfall. Egyptians knew the importance of the stage measurement of rivers and records of the stages of the Nile dating back to 1800 BC have been located. The knowledge of the hydrologic cycle came to be known to Europe much later, around AD 1500 (Subramanya 2010).

In recent times, the issues related to the optimal design of water quality monitoring networks and efficiency improvements have been the subject of research since 1970s (Ning and Chang 2002) and the basic principles of monitoring network design and site selection criteria for individual monitoring stations have been evaluated and applied by many researchers (Skalski and Mackenzie 1982; Lettenmaier et al. 1986; Smith and McBride 1990). Later studies have focused greater attention on the effective design of water quality monitoring networks using various types of statistical and/or programming techniques, such as integer programming, multi-objective programming, Kriging theory and optimization analysis (Hudak et al. 1995; Dixon and Chiswell 1996; Timmerman et al. 1997).

In India, various water monitoring and water supply organizations and institutions are more concerned to monitor the water resources more accurately and on wider geographic region, and thus strengthening their monitoring network from time-to-time. Such agencies and researchers are monitoring precipitation (in the form of rainfall and snow), stream flow (CPCB 2009; Sargaonkar and Deshpande 2003; Samantray et al. 2009; Jindal and Sharma 2011), groundwater (Krishan et al. 2013, 2014, 2015, 2016a; Lapworth et al. 2015; MacDonald et al. 2015), lakes and reservoirs, as well as water quality of various water bodies (Krishan et al. 2016b; Rao et al. 2016).

The design of a hydrometric network starts ideally with a minimum number of stations and increases gradually until an optimum network is attained when the amount and quality of data collected and information processed is economically justifiable and it meets the user's needs to make specific decisions. Network planning is the backbone of any monitoring system. In hydrology, monitoring of data is mostly site-specific and proper representation of this data on spatial scale requires proper network planning. The present paper is in the context of identifying and planning of water quality monitoring network for data acquisition for Integrated Water Resources Management (IWRM).

Water Quality Monitoring Network

Water sample collection network is quite general in nature which may include a network for collection of wide variety of samples. The samples collected under this network may be used for various hydrological analysis, viz. water quality, isotopic analysis, sedimentation, etc.

There are several approaches to water quality monitoring. Monitoring can be done through a network of strategically located long-term stations, by repeated short-term surveys, or a combination of these two. In addition to the basic objectives of the water quality monitoring programme, the location of stations should take into account the following factors:

- Existing water problems and conditions;
- Potential growth centres (industrial and municipal);
- Population trends;
- Climate, geography and geology;
- Accessibility:
- Available manpower, funding, field and laboratory data handling facilities;
- Inter-jurisdictional considerations;
- Travel time to the laboratory (for deteriorating samples); and
- Safety of personnel.

Water Quality Parameters

The parameters that characterize water quality may be classified in several ways, including physical properties (e.g. temperature, electrical conductivity, colour, turbidity), inorganic chemical components (e.g. dissolved oxygen, chloride, alkalinity, fluoride, phosphorous, metals), organic chemicals (e.g. phenols, chlorinated hydrocarbons, polycyclic aromatic hydrocarbons and pesticides), and biological components, both microbiological, such as faecal coliforms, and macrobiotic, such as worms, plankton and fish, which can indicate the ecological health of the aquatic environment (WMO 1994).

A second classification is done according to the importance attached to the parameter. This will vary with the type of water body, the intended use of the water and the objectives of the monitoring programme. Water quality variables are sometimes grouped within following two categories:

(a) Basic variables (given in Table 1).
(b) Use-related variables:
    - Drinking water supplies
    - Irrigation, and
    - General quality of aquatic life.

Table 1 Water quality basic variables

S. No.	Parameters	River	Lake and reservoir	Groundwater
A	*General water quality*			
1	Water level/discharge	X	X	X
2	Total suspended solids	X	–	–
3	Temperature	X	X	X
4	pH	X	X	X
5	Electrical conductivity	X	X	X
6	Dissolved oxygen	X	X	X
7	Transparency	–	X	–
B	*Dissolved salts*			
8	Calcium	X	X	X
9	Magnesium	X	X	X
10	Sodium	X	X	X
11	Potassium	X	X	X
12	Chloride	X	X	X
13	Fluoride	–	–	X
14	Sulphate	X	X	X
15	Alkalinity	X	X	X
C	*Nutrients*			
16	Nitrate plus Nitrate	X	X	X
17	Ammonia	X	X	X
18	Total phosphorous, dissolved	X	X	–
19	Total phosphorous, particulate	X	X	X
20	Total phosphorous, unfiltered	X	X	–
21	Silica reactive	X	X	–
D	*Organic matter*			
22	Chlorophyll *a*	X	X	–

Note ‘X’ = Required; ‘–’ = not required

USDA (2007) has suggested the following general groups of indicators for groundwater quality monitoring programmes:

1. Field measurements (temperature, specific conductance, pH, Eh (redox potential), dissolved oxygen, alkalinity, and depth to water).
2. Major inorganic ions and dissolved nutrients (total dissolved solids (TDS), Cl^-, NO_3^-, SO_4^-, PO_4^-, SiO_2, Na^+, K^+, Ca^{++}, Mg^{++}, NH_4^+).
3. Total organic carbon (TOC).
4. Pesticides (AlphaBHC, betaBHC, gammaBHC, Chloropyriphos, Acetanilide, Triazine, Phthalate, Dinitrophenol, Carbamate, Halocarbon, etc.).
5. Volatile organic carbon (VOC).
6. Metals and trace elements (Fe, Mn, Zn, Cd, Pb, Cu, Cr, Ni, Ag, Hg, As, Sb, Se, Be, B).

7. Bacteria (Coliform bacteria, *E. coli*, Entrococci, etc.).
8. Radionuclides (Radium Radon, Uranium).
9. Environmental isotopes (H, O, N, C, S).

Techniques for Water Quality Monitoring Network Design

Following factors need to be considered for planning of the water quality monitoring network:

1. Monitoring of bedrock and superficial aquifers
2. Depending on hydrological structures
3. Based on water use and site condition
4. Based on mixing of water
5. Based on specific yield
6. Based on flow capacity of river
7. Based on water surface area of lake and reservoir
8. Parallel to coastline
9. Based on land use
10. Based on areal extent

Monitoring of Bedrock and Superficial Aquifers

The proposed network must reflect the diverse hydrogeological, soil and land-use conditions. Therefore, both bedrock and superficial aquifers should be monitored in a variety of soil conditions. The network should continue to include different types of sources, although less emphasis should be given to wells, which are generally poor monitoring points. The nature of water quality in these two types of aquifers generally differs significantly, and hence water quality monitoring is essential.

Depending on Hydrological Structures

The number of sampling points on a river depends on the hydrology and the water uses. The greater the water quality fluctuation, the greater the frequency of measurement required. In humid regions, where concentrations of dissolved matter are low, fewer observations are needed than in dry climates, where concentrations, particularly of critical ions such as sodium, may be high. At many locations, the water quality sampling stations may be coupled to the stream gauging stations and structures such as barrage, dams, etc. Similarly, the gauging sites of the spring flow may also be used for the water sampling purpose.

Based on Water Use and Site Condition

For establishing water sampling stations on water use and site conditions, the areas need to be sampled to assess the extent and severity of contamination on the basis of sources such as anthropogenic or geologic water quality pollution or contamination due to particular rock formations. If any water supply scheme or any waste water disposal site exists there, then such sites need to be critically mapped.

Based on Mixing of Water

On rivers, the sampling stations should be established at places where the waste water is sufficiently well mixed with it. Since the lateral and vertical mixing of a wastewater effluent or a tributary stream with the main river can be rather slow, particularly if the flow in the river is laminar and the waters are at different temperatures and complete mixing of tributary and main stream waters may not take place for a considerable distance, sometimes many kilometres, downstream of the confluence, therefore, the zone of complete mixing may be estimated from the values shown in Table 2 (UNEP/WHO 1996). In the case of doubt, the extent of mixing should be checked by measurements of temperature or some other characteristic variables at several points across the width of the river (Krishan et al. 2016b). If there

Table 2 Estimated distance of complete mixing in streams and rivers

Average river width (m)	Mean depth of river (m)	Estimated distance for complete mixing (km)
5	1	0.08–0.7
	2	0.05–0.3
	3	0.03–0.2
10	1	0.3–2.7
	2	0.2–1.4
	3	0.1–0.9
	4	0.08–0.7
	5	0.07–0.5
20	1	1.3–11.0
	3	0.4–4.0
	5	0.3–2.0
	7	0.2–1.5
50	1	8.0–70.0
	3	3.0–20.0
	5	2.0–14.0
	10	0.8–7.0
	20	0.4–3.0

are rapids or waterfalls in the river, the mixing will be speeded up and representative samples may be obtained downstream. Sampling for the determination of dissolved oxygen, however, should take place upstream of the rapids or waterfall because the turbulence will cause the water to be saturated with oxygen. In such a case, several samples should be taken across the width of the river to allow for the possibility of incomplete mixing.

A bridge is an excellent place to establish a sampling station (provided that it is located at a sampling site on the river). It is easily accessible and clearly identifiable location. Furthermore, a bridge is often a hydrological gauging station and, if so, one of the bridge piers will have a depth gauge marked on it, thus allowing the collection of stream flow information at the time of sampling. Usually, a sample taken from a bridge at mid-stream or in mid-channel, in a well-mixed river, will adequately represent all of the water in the river.

To verify that there is complete mixing at a sampling station it is necessary to take several samples at points across the width and depth of the river and to analyse them. If the results do not vary significantly one from the other, a station can be established at mid-stream or some other convenient points. If the results are significantly different it will be necessary to obtain a composite sample by combining samples taken at several points in the cross section of the stream. Generally, the more the points that are sampled, the more representative the composite sample will be. Sampling at 3–5 points is usually sufficient and fewer points are needed for narrow and shallow streams. Suggestions are provided in Table 3 for the number of points from where samples should be obtained in streams or rivers of different sizes and with different flow rates.

Based on Specific Need

Water quality sampling stations may also be required to be fixed based on the need. Such needs may arise due to any or some of the reasons mentioned below:

1. Occurrence of health problems in a particular area.
2. Drinking water supply scheme.
3. Research needs.
4. Waste water disposal in a stream.
5. Just before an international boundary, if the river is draining outside the country.
6. Just after an international boundary, if the river is entering into the country.
7. Just before or after the inter-state boundary, if the river is draining in more than one state.
8. Above the points of withdrawal for irrigation, or domestic, or industrial purpose under a major scheme.
9. Outlets of lakes and reservoirs.

Based on Flow Capacity of River

Lakes and reservoirs can be subjected to several influences that cause water quality to vary from place to place and from time-to-time. It is, therefore, prudent to conduct preliminary investigations to ensure that sampling stations are truly representative of the water body. Where feeder streams or effluents enter lakes or reservoirs, there may be local areas where the incoming water is concentrated, because it has not yet mixed with the main water body. Isolated bays and narrow inlets of lakes are frequently poorly mixed and may contain water of a different quality with the rest of the lake. Wind action and the shape of a lake may lead to a lack of homogeneity; for example, when wind along a long, narrow lake causes a concentration of algae at one end. Table 3 suggests the sampling regimes for composite samples in the flowing water.

In India, a vast river quality monitoring data has been accumulated over the years but it has not been properly utilized for reasons of limited ability to communicate the data to the common man. Some researchers have tried to use the river water quality indices with limited success (Sargaonkar and Deshpande 2003; Samantray et al. 2009; Jindal and Sharma 2011).

Based on Water Surface Area of Lake and Reservoir

A number of sampling locations vary with the size and depth of any water body. If the water surface area of lake or reservoir is large enough, multiple sampling locations are necessary. To allow for the size of a lake (UNEP/WHO 1996) has suggested that the number of sampling stations should be the nearest whole number to the log10 of the area of the lake in km^2. Thus, a lake of 10 km^2 requires one sampling station, 100 km^2 requires two stations, and so on. For lakes with irregular boundaries, it is advisable to conduct preliminary investigations to determine whether and where differences in water quality occur before deciding on the number of stations to establish.

The most important feature of water in lakes and reservoirs, especially in temperate zones, is vertical stratification, which results in differences in water quality at different depths (UNEP/WHO 1996). Stratification at a sampling station can be detected by taking a temperature reading at 1 m below the surface and another at

Table 3 Suggested sampling regimes for composite samples in flowing water (UNEP/WHO 1996)

Average river discharge (m^3/s)	Type of stream/river	Number of sampling points	Number of sampling depths
<5	Small stream	2	1
5–140	Stream	4	2
150–1000	River	6	3
≥ 1000	Large river	≥ 6	4

1 m above the bottom. If there is a significant difference (e.g. >3 °C) between the surface and the bottom readings, there is a "thermocline" (a layer where the temperature changes rapidly with depth) and the lake or reservoir is stratified and it is likely that there will be important differences in some water quality variables above and below the thermocline. Consequently, in stratified lakes, more than one sample is necessary to describe the water quality. For lakes or reservoirs of ≥ 10 m depth it is essential, therefore, that the position of the thermocline is first investigated by means of regularly spaced temperature readings through the water column (e.g. metre intervals). Samples for water quality analysis should then be taken according to the position and extent (in depth) of the thermocline. As a general guide, the minimum samples should consist of

- m below the water surface,
- just above the determined depth of the thermocline,
- just below the determined depth of the thermocline, and
- m above the bottom sediment (or closer if this can be achieved without disturbing the sediment).

If the thermocline extends through several metres depth, additional samples are necessary from within the thermocline in order to characterize fully the water quality variations with depth. Whilst the position of the thermocline is stable, the water quality for a given station may be monitored by fewer samples but, in practice, the position of a thermocline can vary in the short- (hours) or long-term (days) due to internal seiches (periodic oscillations of water mass) and mixing effects. In general, in tropical climates where the water depth at the sampling site is <10 m, the minimum sampling should consist of a sample taken 1 m below the water surface and another sample taken at 1 m above the bottom sediment.

Parallel to Coastline

Sea water intrusion is the most common problem in the coastal aquifers. Without salinity monitoring of groundwater in the coastal aquifers, it is not impossible to decide on the sea water intrusion. It is thus imperative to have a good network of observation wells in the coastal aquifers particularly parallel to the coastline. The groundwater table is very shallow near the coast and goes down below the land surface on moving away from the coast. For monitoring the dynamics of saline and fresh water interface, at least 03 observation wells should be placed perpendicular to the coastline at regular intervals, either fixed or depending on rock formations susceptible to the sea water ingress, withdrawal patterns in the aquifers, etc. The 03 observation wells shall be placed at 2, 4 and 6 km away from the coastline for the salinity monitoring.

Table 4 Recommended minimum density of water quality stations (WMO 1994)

S. No.	Physiographic unit	Minimum density per station (km^2/station)
1	Coastal	55,000
2	Mountainous	20,000
3	Interior plains	37,500
4	Hilly/Undulating areas	47,500
5	Small islands	6,000
6	Polar/Arid regions	200,000

Based on Land Use

The effluents from the domestic, industrial and agricultural activities pose large influence on the surface and groundwater resources in the surrounding areas. Many times, land use has a large influence on the nitrate concentrations in arable areas, cultivation of both arable and grassland, and areas where dairy, pigs and poultry contribute to the highest nitrate concentrations. Thus, proper monitoring network is required under such nitrate pressured areas. Thus one sampling site should be located in each land-use class which is representative of that class for the region.

Similar kinds of monitoring networks are also required to other industrial areas where the industrial effluents may affect the water resources depending on the nature of the industries.

Based on Areal Extent

For small streams, a sampling procedure becomes necessary as it is impracticable to establish gauging stations on all of them. The discharge of small rivers is strongly influenced by local factors. In highly developed regions, where even the smallest watercourses are economically important, network deficiencies are keenly felt even on streams draining areas as small as 10 km^2. WMO (1994) has recommended the minimum density of water quality stations as given in Table 4.

Conclusions

Quantity and quality of surface and groundwater vary from place to place depending on several morphological and hydrogeological factors. The quality of water may further be subjected to various anthropogenic activities and transport of pollutants varies both in space and time. Proper monitoring of such phenomena requires well-organized and optimized monitoring network that is the true representation of the water quality of that region. Therefore, proper monitoring network must be dependent on spatial hydrogeological factors with due diligence to the anthropogenic sources including the intended use of the monitoring network. Thus a well-planned water quality monitoring network for Integrated Water Resources Management (IWRM) can be achieved (i) if goals are clear, defined and well developed; (ii) the hydrogeology and geology of the aquifer formation is well understood and taken into consideration; (iii) the budgetary constraints are looked into; and (iv) some statistical techniques for optimization of network. Various techniques for planning and identification of the monitoring points and water quality parameters to be included are presented and discussed in the paper.

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References

CPCB, Central Pollution Control Board (2009) National Water Quality Monitoring Programme. http://www.cpcb.nic.in/divisionsofheadoffice/pams/NWMP.pdf

Dixon W, Chiswell B (1996) Review of aquatic monitoring program design. Water Res 30:1935–1948

Hudak PF, Loaiciga HA, Marino MA (1995) Regional-scale ground water quality monitoring via integer programming. J Hydrol 164:153–170

Jindal R, Sharma C (2011) Studies on water quality of Satluj river around Ludhiana with reference to physic-chemical parameters. Environ Monit Assess 174(2):417–425

Krishan G, Lohani AK, Rao MS et al (2013) Optimization of groundwater monitoring network in Bist-Doab, Punjab. In: Proceedings of an international conference “India Water Week 2013-Efficient Water Management: Challenges and Opportunities” (IWW-2013), 08–12 April 2013 at New Delhi, India, pp 274

Krishan G, Lohani AK, Rao MS, Kumar CP (2014) Prioritization of groundwater monitoring sites using cross-correlation analysis. NDC-WWC J 3(1):28–31

Krishan G, Singh RP, Takshi KS (2015) Water level fluctuation as the sum of environmental and anthropogenic activities in Southeast, Punjab (India). J Environ Anal Toxicol 5:298

Krishan G, Singh S, Kumar CP, Garg PK, Gurjar S, Ghosh NC, Chaudhary A (2016a) Assessment of groundwater quality for drinking purpose using water quality index in Muzaffarnagar and Shamli districts, Uttar Pradesh, India. Hydrology. Current Research 7:1. doi:10.4172/2157-7587.1000227

Krishan G, Singh S, Sharma A, Sandhu C, Grischek T, Gurjar S, Kumar S, Singh RP, Glorian H, Bornick H (2016b) Assessment of river quality for river bank filtration along Yamuna River in Agra-Mathura districts of Uttar Pradesh. Int J Environ Sci 7(1):56–67

Lapworth DJ, MacDonald AM, Krishan G, Rao MS, Gooddy DC, Darling WG (2015) Groundwater recharge and age-depth profiles of intensively exploited groundwater resources in northwest India. Geophys Res Lett 42(18):7554–7562. doi:10.1002/2015GL065798

Lettenmaier DP, Anderson DE, Brenner RN (1986) Consolidation of a stream quality monitoring network. Water Resour Bull 22:1049–1051

MacDonald AM, Bonsor HC, Taylor R et al (2015) Groundwater resources in the Indo-Gangetic basin—resilience to climate change and abstraction. British Geological Survey Open Report, OR/15/047, 63 pp

Ning SK, Chang NB (2002) Multi-objective, decision-based assessment of a water quality monitoring network in a river system. J Environ Manage 4:121–126

Rao MS, Sampath K L, Rangaraj C et al (2016) Application of isotopes in studying lake water – groundwater interactions in parts of Tumkur district of Karnataka. Curr World Environ. 11(3): 751-755

Samantray P, Mishra BK, Panda CR, Rout SP (2009) Assessment of water quality index in Mahanadi and Atharabanki rivers and Taldanda Canal in Paradip area, India. J Hum Ecol 26 (3):153–161

Sargaonkar A, Deshpande V (2003) Development of an overall index of pollution for surface water based on a general classification scheme in Indian context. Environ Monit Assess 89 (1):43–67

Skalski JR, Mackenzie DH (1982) A design for aquatic monitoring programs. J Environ Manage 14:237–251

Smith DG, McBride GB (1990) New Zealand's national water quality monitoring network—design and first year's operation. Water Resour Bull 26:767–775

Subramanya K (2010) Engineering hydrology, 3rd edn. Tata McGraw Hill Publishers, New Delhi

Timmerman JG, Adriaanse M, Breukel RMA, Van Oirschot MCM, Ottens JJ (1997) Guidelines for water quality monitoring and assessment of transboundary rivers. Euro Water Pollut Control 7:21–30

UNEP/WHO (1996) Water quality monitoring—a practical guide to the design and implementation of freshwater quality studies and monitoring programmes, Jamie Bartram and Richard Balance, eds, Published on behalf of United Nations Environment Programme and the World Health Organization, ISBN 0 419 22320 7 (Hbk) 0 419 21730 4 (Pbk)

USDA (2007) United States Department of Agriculture, Technical Guide to Managing Ground Water Resources, FS-881

World Meteorological Organization (WMO) (1994) Guide to hydrological practices. WMO-164, 5th edn. WMO-No. 168, Geneva, Switzerland