Water Quality Monitoring System Design

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1.0 INTRODUCTION

Water influences natural systems and human activities in the context of a river basin. In turn, natural water systems are shaped by their physical basins, human use, environmental changes and climate systems. As the Earth's population and the resulting anthropogenic footprint and impact on climate increase, the need to maintain and protect freshwater resources gains importance for sustainable development, balancing social needs with economic development and environmental stewardship. In 2011, the World Economic Forum (WEF) identified the interconnected resource issues of water, energy and food as a serious global risk and indicated that managing one aspect of this interrelated system without considering links to the others increases the global risk of serious unintended consequences. Indeed, not managing water and natural resources properly has led to the decline or collapse of civilizations.

The International Institute for Sustainable Development (IISD) has been highlighting the need to address water-energy-food (WEF) challenges in the contexts of communities and watersheds to ensure that ecosystems comprising land and water systems are managed for their full range of benefits, ensuring these critical components of human security. For example, fresh water, agricultural productivity, habitat, natural resources, hydroelectricity, etc. are all benefits that must be considered and managed carefully to ensure human and related ecosystem security now and into the future. Mining is a particular form of development that has a unique set of impacts and implications for water quantity and quality. For example, pollution associated with mining can affect both the long-term viability of the mine and the water and food sources of local communities. With an increased demand for minerals, metals and other mined products, understanding these impacts and managing them to the best possible extent is important to maintaining sustainability in mining systems.

In examining WEF security, IISD believes that it is important to understand: i) the availability of WEF sources, (ii) access to WEF sources, (iii) supporting infrastructure and (iv) supporting institutions and policies that influence these systems. Details of these components of WEF are provided in IISD's Water-Energy-Food Resource Book for Mining.

The Role of Monitoring Systems

A key component of managing WEF security is understanding the component systems, how they are functioning and how they respond to development, climate and other pressures. To effectively manage WEF security for a community or region, one needs to monitor and understand each of the three systems. Understanding each system accurately in turn relies on monitoring and reporting of system parameters. To provide guidance on effective and high-quality monitoring, this report focuses on the details of water monitoring, including issues such as monitoring system design, site selection, monitoring frequency, reporting, etc. to enhance its ability to inform water and watershed management.

This report begins with a broad explanation of the water cycle (Section 2.1), indicating briefly how parameters of the water system affect interlinked food and energy systems. The report then provides detailed guidance on water monitoring as a means of measuring and managing the benefits that contribute to regional security. Characterization of water systems requires monitoring of the flow, storage and use of water, and comprehensive watershed monitoring inevitably incorporates socioeconomic parameters along with the more typical biophysical ones.

There is a fair amount of literature on methods, and best management practices exist for establishing water-monitoring systems. These systems, known as Hydrologic Information Systems (HISs), are a crucial element in the wise management of water resources.

Helpful resources on the topic are:

- A *Primer on Hydrologic Measurement Systems: Data Acquisition and Real-Time Telemetry* (Haeggli, 2009), a report for the World Bank Support for Real-Time Hydrologic Systems for HP-II
- *Standards for the Analysis and Processing of Surface-Water Data and Information Using Electronic Methods: U.S. Geological Survey, Water-Resources Investigations Report 01–4044* (Sauer, 2002)
- *Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes* (United Nations Environment Programme [UNEP] & World Health Organization [WHO], 1996b)
- *Water Measurement Manual (3rd edition). U.S. Department of the Interior, Bureau of Reclamation, A Water Resources Technical Publication* (United States Bureau of Reclamation, 2001)
- *Guide to Hydrological Practices: Data Acquisition and Processing, Analysis, Forecasting and other Applications* (5th ed.) (World Meteorological Organization [WMO], 1994)
- National Hydrology Project, Hydrologic Information Systems (World Bank, 2015)

Beyond measuring water quantity and quality conditions, HISs are concerned with the processing, storage, analysis, reporting and dissemination of hydrologic data. Developing an HIS involves careful consideration of the purpose; network design; data collection, quality checking and storage; and dissemination to end users. Extensive documentation has been developed on the designing, sampling methodology and procedures, as well as institutions of HIS and instrumentation. Though available, the information is disseminated among a large number of manuals and presentations, making it difficult to readily take in. This document consolidates the information into a single overview that users can reference when designing an HIS network. It also provides recommendations to more comprehensive references in instances where users need more detailed information.

2.0 HYDROLOGIC INFORMATION SYSTEM (HIS) OVERVIEW

2.1 Hydrology and the Water Cycle

The water cycle, or hydrologic cycle, is the circulation of water through the atmosphere, land, ground, riverine network and oceans (Figure 1). Moisture in the atmosphere condenses, falling to the Earth's surface as rain, snow and sleet or condensing from fog drip and dew. Precipitation hitting the surface of condensation ponds runs off over land or infiltrates into the ground. Portions of the ponded water and runoff evaporate and infiltrated water evaporates or is transpired by plants back into the atmosphere (the process is collectively referred to as evapotranspiration). Excess water enters the riverine systems of streams, lakes and rivers (surface water system), or infiltrates through the unsaturated groundwater zone into the saturated groundwater zone (groundwater systems). In both systems, water travels "downstream" towards the oceans with the two systems exchanging water in the process. In addition, people influence the water flow toward the oceans through diverting, damming, pumping, channelizing and consuming to support human needs such as irrigation, domestic, commercial, municipal, industrial, energy production and navigation uses. Unconsumed and post-consumed water by humans re-enters the groundwater and surface water systems in its travels. Water that has neither been lost to evapotranspiration, nor stored in reservoirs, glaciers or aquifers, nor consumed by people enters the ocean where it again is evaporated to supply the atmospheric moisture that will ultimately precipitate or condense. Throughout the process, water quantity and chemistry are changing.

The science of understanding the occurrence, distribution, movement and properties of water and its relationship with the environment is called *hydrology*.

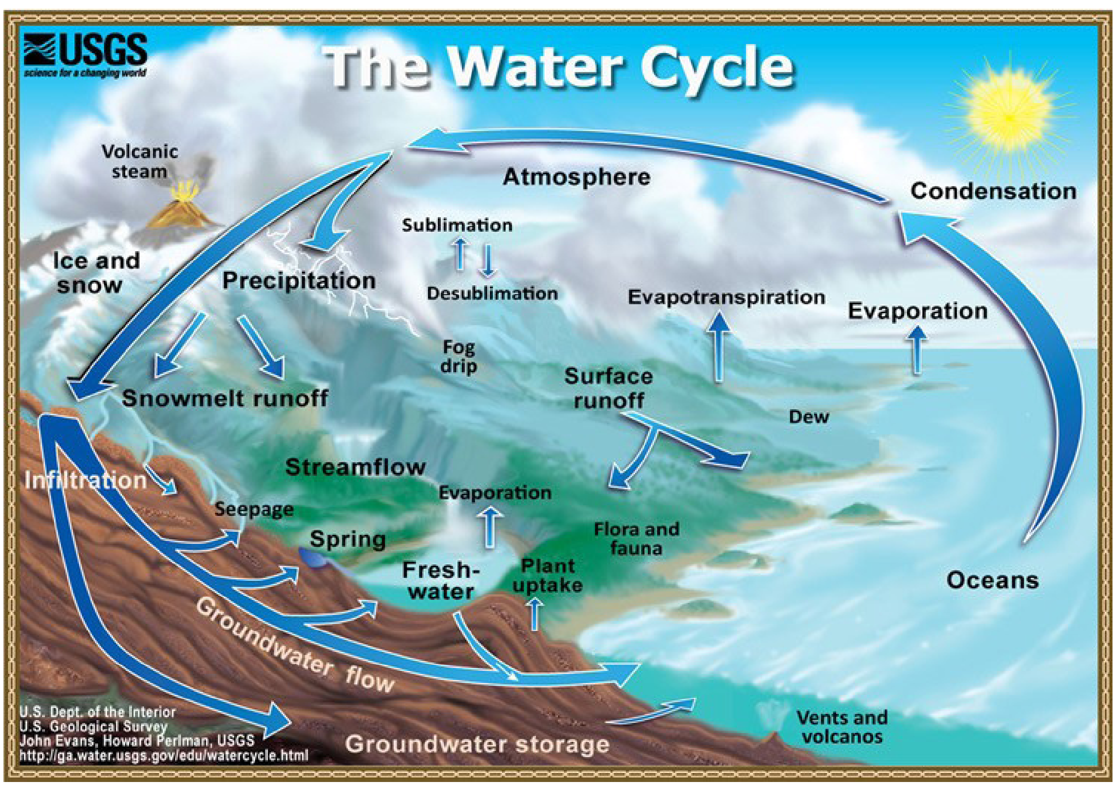

Figure 1. Graphical depiction of the water cycle. Source: U. S. Geological Survey
Source: U. S. Geological Survey (2015)

Human well-being relies on water and the ecosystems that it supports. The delivery, timing, storage and quality of water in a watershed influence the social, economic and ecological systems that influence people's lives. Water managers are concerned with the quantity and quality of water as it moves through the cycle and how policies, projects and infrastructure operations can be operated to improve human well-being. A key component of managing water is characterizing the flow, storage and quality of the water within the basin. Better understanding of a basin's hydrologic cycle, as well as human and ecosystem use of water, greatly improves planning efforts; reduces risk and cost in the design and operation of infrastructure (e.g., reservoirs); decreases damages associated with flooding and drought; and improves policies for managing the water resources in a basin. The fundamental method for understanding the hydrologic cycle in a basin is monitoring water quantity and the quality of its movement in the groundwater and surface water systems. Thus, an effective monitoring system is key to better water management in a basin.

2.2 HIS Definition

A Hydrologic Information System (HIS) is a system for measuring, processing, storing and disseminating interlinked aspects of watershed data including the quantity and quality of climate (hydro-meteorological, e.g., precipitation, evapotranspiration), surface water (hydrological) and groundwater (hydrogeological). Elements of an HIS include the physical infrastructure and human resources (United Nations environment Programme [UNEP] & World Health Organization [WHO], 1996). The physical infrastructure includes observation networks; laboratories; data communication systems and data storage; and processing centres equipped with databases and tools for data entry, validation, analysis, retrieval and dissemination (UNEP & WHO, 1996). Human resources are well-trained, dedicated staff supporting the HIS with a variety of skills to observe, validate, process, analyze and disseminate the data. Failure to address either element in developing a monitoring system will limit the success of implementing an HIS. This report focuses on surface water, groundwater and water-quality monitoring in distinct sections.

2.3 HIS Role in Water Management

Watershed management involves managing the land, water systems and freshwater ecosystems to protect and improve water quality and quantity for supporting the ecological, social and economic systems within a watershed. Water-related decision-makers are concerned with ensuring that these benefits are maintained and optimized against other uses and over time. A critical need for good watershed management is comprehensive data, characterizing the hydrologic system and its main components and links. An HIS is a critical component of watershed management and decision-making, as it compiles and provides the data and information necessary for informed decision-making, monitors the impacts of programs and other actions, and helps us understand trends and in watershed and component systems.

A robust HIS network provides information to give water managers and interested stakeholders a means of monitoring, evaluating and analyzing the hydrologic system upon which ecological, social and economic systems rely. HIS data support a wide gamut of water projects, from long-term planning to infrastructure design to real-time operations to research (Table 1). Incorporating spatial and temporal data into water projects increases the predictive accuracy, lowers the risk, provides greater economic benefit (i.e., more efficient designs, operations and water use), reduces potential for conflict and provides the foundation for better decisions (World Bank, 2015). Continuous collected field measurements are evaluated either as is or statistically converted (e.g., maximum values, minimum, frequency of occurrence, trends, seasonality), depending on the question being addressed and the analysis being performed.

Table 1. Priority of hydrologic and water quality monitoring data in water projects.

Water projects	*Water levels*			*River flow*			*Sediment*			*Water quality*[a]		
	time series	*max*	*min*	*time series*	*max*	*min*	*time series*	*max*	*min*	*time series*	*max*	*min*
Redistribution of water (diversions, intakes, canals)	M	M	M	H	H	H	H	M	M	H	M	M
Redistribution of water in time (reservoirs)	M	M	M	H	H	H	H	M	M	H	M	M
Energy production (hydropower, waste heat disposal)	H	M	M	H	M	H	H	M	M	M	M	M
Water confiners (dams, flood banks)	H	H	M	M	H	M	M	M	M	M	M	M
Water relievers (spill ways)	M	H	M	H	H		M			M		
Quality improvements (water and sewage treatment)				H	M	H	M	M	M	H	H	H
Zoning (flood plain, scenic rivers)	H	H	M	M	H	M	M					
Insurance (flood damage, water quality damage)	H	H		H	H					H	H	
Flow and level forecasts (flood control, reservoir operation)	H	H	H	H	H	H						
Standards and legislation (water quality)	M	H	H	M	H	H				H	H	H

[a] Water-quality parameters are diverse depending on the type of project.
H = High level of priority   M = Medium level of priority

Source: WMO (2008)

2.4 Developing a Monitoring Network

A key component of an HIS is the monitoring network, which involves collection of field measurements. The fundamental factors influencing the design of a monitoring network is the monitoring objectives (present and future), physical characteristics of the systems and resources available (human and monetary) (UNEP & WHO, 1996). The first step in developing an HIS is to determine the purpose of the monitoring. For example, is the monitoring network supposed to characterize baseline conditions in a watershed over time, ascertain the impacts of climate change on human development, monitor the impact of a certain project on the water system or a combination of all the purposes. Based on the specific objectives and timescale, what is to be sampled, where, how often and how accurate the sample collection can be determined. Choosing the appropriate scale and scope depends on the monitoring objectives and budgetary/resource constraints. Costs associated with establishing and operating a monitoring network include land acquisition, station construction, equipment procurement and installation, station operation, maintenance, data processing and storage, and staffing of field stations and data centres. Once the relationship between the chosen effectiveness measure and costs has been established, the optimal network can be found.

Monitoring objectives influence the density of monitoring stations and the duration of operations. Monitoring network types can be classified as baseline, management and project.

- **Baseline**: A low network density of monitoring stations and a long period of operations characterize baseline networks in order to provide a synoptic data set.
- **Management**: *Management* networks address water resource issues by supplementing the baseline network with increased monitoring stations that are subject to alteration (station locations and variables) to address changing conditions in management of resources.
- **Project**: *Project* networks are supplemental to baseline and management networks and are installed to assist in planning, operating and monitoring conditions in and around a project or study. The latter would be appropriate for developing, operating and assessing the changes associated with a mine.

Monitoring networks are not static and thus need to be evaluated and altered periodically (World Meteorological Organization [WMO], 1994). Objectives need to be re-evaluated and data need to be reviewed to determine if they are adequately capturing the spatio-temporal variability for managing resources. That said, the long-term baseline network should be maintained with minimal change or disruption in order to provide a long-term record of hydro-meteorological conditions.

2.5 Integration of Monitoring Networks

As most organizations monitor only a limited range of the hydrologic cycle, a monitoring network to support water resource management should have a coordinated approach in measuring the hydro-meteorological, surface water, groundwater and water quality conditions. The *baseline* hydro-meteorological monitoring network should support the surface water and groundwater monitoring networks in determining rainfall-runoff computations and groundwater recharge areas, respectively. For *baseline* surface water monitoring networks, spatial coverage of water level and discharge stations should have sufficient spatial coverage for the computation of catchment water budgets. Similar water balance and resource assessment considerations also apply to the groundwater and water quality monitoring networks. Organizational integration of the networks implies that the networks are complementary and that a regular exchange of field data occurs between agencies to produce authenticated, high-quality data.

A typical example is the hypothetical one depicted in Figure 1, where water managers in the basin are facing a number of watershed management challenges that involve groundwater and surface water quantity and quality issues (World Bank, 2015). These issues include flooding near the city; water allocation between the municipalities, irrigation, industry and ecological sectors; groundwater sustainability for industrial expansion in the proximity of the city; and optimization of reservoir operations to prevent flooding and satisfy downstream water demand requirements during periods of low rainfall. The type of monitoring equipment presented in the example is explained in subsequent chapters.

In order to make water allocation decisions, a series of hydro-meteorological, surface water and groundwater networks have been developed to understand these issues in space and over time. In this example, various departments within the central government have established baseline monitoring networks for the entire country with a limited number of monitoring stations located in this basin. With regards to hydro-meteorological monitoring, the state meteorological department

(SMD) has augmented the central meteorological department's (CMD) automatic rain gauges (ARGs) with 10 additional ARGs to provide a more detailed understanding of the distribution of precipitation for planning, as well as to increase alerting power for flood warning systems. As a greater quantity of and more spatially varied precipitation falls in the mountainous headwaters, a greater density of precipitation gauges have been located in the region, including snow pillows to capture and characterize the snowpack conditions. Automatic weather stations (AWSs) have been installed by the SMD and CMD at the reservoir and in irrigated areas to compute evapotranspiration for seasonal planning of the reservoir and irrigation demands. Given the uniformity of evapotranspiration across the basin, only two AWSs are required to address the water management issues.

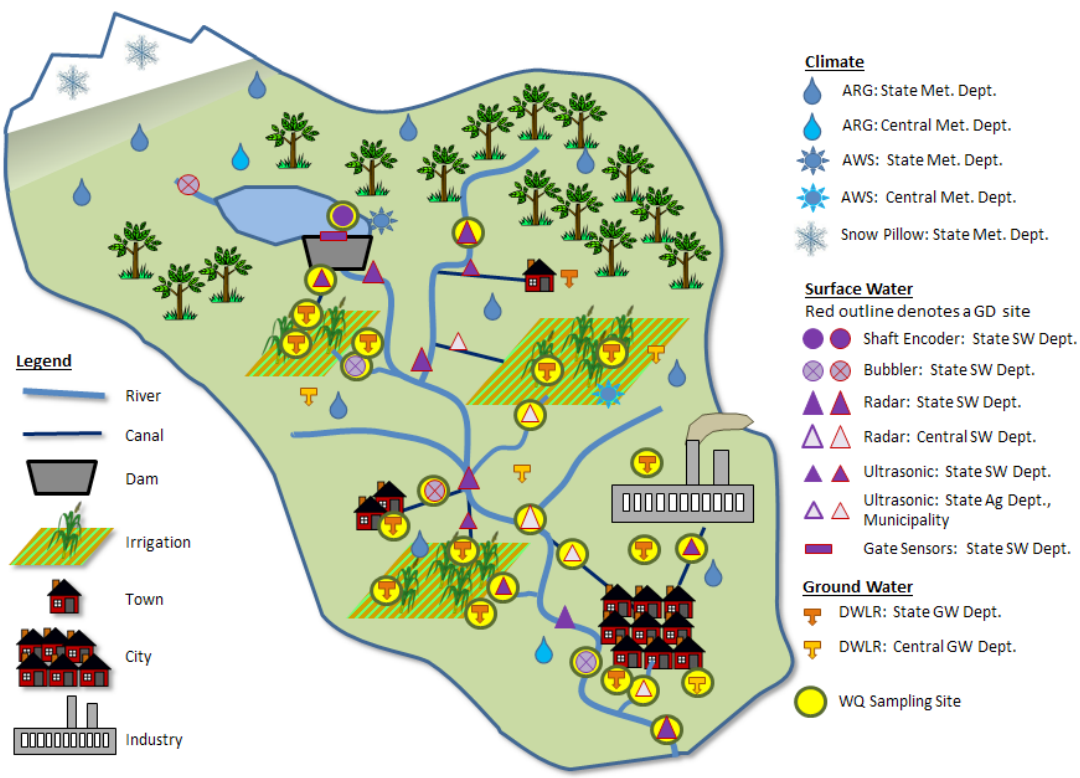

Figure 2. Example basin with climate, surface water and groundwater monitoring networks by multiple agencies. ARG is an automatic rain gauge, AWS is an automatic weather station and DWLR is a digital water level recorder. Stations A-D are referenced in the text.

Source: modified from World Bank (2015)

The surface water monitoring networks in the basin have been established to quantify water distribution in the river system as well as the anthropogenic (human-influenced) withdrawal, consumption and return flow of water (Figure 1). The central surface water department (SWD) operates a gauge on the main river midway along the basin as part of a country-level baseline monitoring system, thus the state SWD has augmented the river gauges to support the management of flooding and water allocation. Gauge-discharge stations have been located at significant junctures along the mainstem as well as significant tributaries to aid in assessing flows for both real-time and planning management. All surface water monitoring stations employ water level recorders with site-specific discharge measurements to develop a stage-discharge rating curve. Where bridges are located, radar sensors have been used, shaft encoders have been used with stilling wells, and bubblers have been used where no structures exist. As flooding is of concern in river reaches near the city, the water level recorders have been placed in the surrounding reach to warn of impending floodwaters (sites A and B). Aside from the central SWD gauge, the gauges have telemetric capabilities as part of the flood warning system.

For reservoir planning and operation, the reservoir and associated canal system supporting the irrigated areas have been further instrumented with telemetry (Site C). The river upstream of the reservoir has been gauged using a bubbler to predict inflow from the major tributary (Site D). A stilling well with a shaft encoder is used to determine the water levels. Near the stilling well is the AWS to predict rainfall and evapotranspiration that is used in reservoir management and long-term planning. Gate sensors, used to measure discharge as a function of gate openings, have been installed on the reservoir's radial gates to aid in operation. Canals leading to the command area are equipped with an ultrasonic water level recorder to determine the flow being released for irrigation. The canals into and out of the irrigation command areas are monitored for both water quality and quantity to evaluate irrigation practices.

Digital water lever recorders (DWLR) monitored by the central groundwater department (GWD) are distributed to regionally characterize the groundwater conditions. Given the irrigation use and industrial expansion concerns with groundwater, the state GWD has increased the density in and around irrigation fields, around towns and cities using groundwater as a drinking source, and in the vicinity of potential industrial development (Sites E). As there are little groundwater resources in the mountains, no DWLRs have been placed there.

Water quality is often monitored at stations where water quantity is also measured, in order to calculate the total load of constituents of concern (CoC). In this basin, the state water quality department monitors water quality in the rivers and groundwater. Water quality is measured upstream and downstream of irrigation, industrial and municipal activities (Sites A, B, C, E). The state public health department monitors drinking water sources from surface diversion and groundwater wells.

In the basin, all central, state and municipal monitoring networks assist water managers in real-time operations and longer-term planning. Individually, the knowledge of water movement from only one network would not provide a comprehensive characterization of water flow, storage and use in the basin. It is by combining resources that more informed decisions can be determined, providing the foundation for better water management.

3.0 HIS DESIGN GUIDELINES

3.1 Elements of HIS Development

HIS development requires the assessment of the user needs; establishment/review of observational networks; implementation of a data management system; data collection; data processing and storage; data dissemination, analysis and reporting; and institutional and human resource development (Figure 2) (WMO, 1994; UNEP & WHO, 1996; World Bank, 2015). To build successful monitoring networks, all aspects of HIS development need to be developed. The following text outlines the primary steps toward HIS development and implementation.

3.1.1 Assessing the User Needs

The first step in HIS development is assessing how the data will be used and who will use it. As seen in Table 1, there is great value in developing a baseline HIS network; however, additional targeted monitoring may be needed to address specific management needs. Therefore, the potential data users should be consulted at the onset of HIS development to ascertain their needs. From these needs, priorities can be identified and the HIS network created to support the objectives of multiple stakeholders. This step is very important for the relevance and longevity of the monitoring network as well as illuminating potential collaborations in collecting water quantity and quality data.

3.1.2 Establishment/Review of Observational Networks

Following a user needs assessment, the observational network has to be accordingly planned, designed and established/upgraded/adjusted. Objectives and data collection from the multiple stakeholders should be considered to avoid duplication of monitoring when identifying monitoring site locations and selecting monitoring equipment. Location, types, measurement frequency and period of record of historical data collection should also be considered in the monitoring network design. As budgetary and resource limitations may constrain the number of locations, the objectives should be prioritized before network design in order to ensure that monitoring network addresses the top issues. Often, collaboration of monitoring between multiple agencies can yield a more robust monitoring network. The process should be repeated after periodic reviews of requirements.

3.1.3 Implementation of a Data Management System

Equally important to the data collection is the storage and management of data in a data management system (DMS). A DMS is a computerized database that allows for the storage, management, quality assurance and dissemination of the data. The types of data stored in the database include: geographical and space-oriented data (e.g., GIS information and location of observation stations), time-oriented data (e.g., time series of meteorological, climatic, water quantity, water quality and sediment data) and relation-oriented data (e.g., processed data and analysis). Historic data should be added to the database and the database should include a link to mapping functionality as well. Establishment of a DMS is essential for the long-term sustainability of the data sets in proper form and their dissemination to the end users. Commercial and open-source DMSs are available to support this requirement.

3.1.4 Data Collection

Following the monitoring network installation and DMS construction, data collection ensues. Data are collected and supplied to the DMS electronically or measured and entered by trained staff. Timely submittal of the data is important to detect malfunctioning equipment and address water-related issues.

3.1.5 Data Processing and Storage

Data processing involves receiving records of observed field data, performing validation checks, infilling missing values in a data series, compiling data in different forms and analyzing the data to support decision-making (Terakawa, 2003). In the process, the data must be validated for quality and reliability, as errors can occur in the monitoring sensor, data recorder, interruptions in transmission and human entry. Field data, as observed and recorded, may contain many gaps and inconsistencies that must be identified, flagged and, if possible, corrected so that users understand the quality of the data. Data processing activities are typically carried out at more than one level within an implementing agency, making it essential to have adequate data transport/communication links between them. Functionality in many DMSs supports the processing. Protocols must be established for the long-term use and archiving of the observed and processed data.

3.1.6 Data Dissemination, Analysis and Reporting

Processed data can be presented directly to the user or given in the form of analysis or reports. Analysis and reports require customization to ensure the reported information is relevant to user needs. The use of intranet and Internet systems facilitates the data dissemination and exchange. For example, a web portal allows anyone to identify and download the large amounts of monitoring data collected by the USGS as well as the reports they generate.

3.1.7 Institutional and Human Resources Support

Institutional, human and budgetary supports are a prerequisite for smooth operation and maintenance of the observation stations and the associated collection of data (World Bank, 2015). The institutions supporting the HIS must be developed in such a manner that the system is sustainable in the long run. The staff carrying out different activities under HIS are to be made available and must have the essential training to carry out the desired tasks.

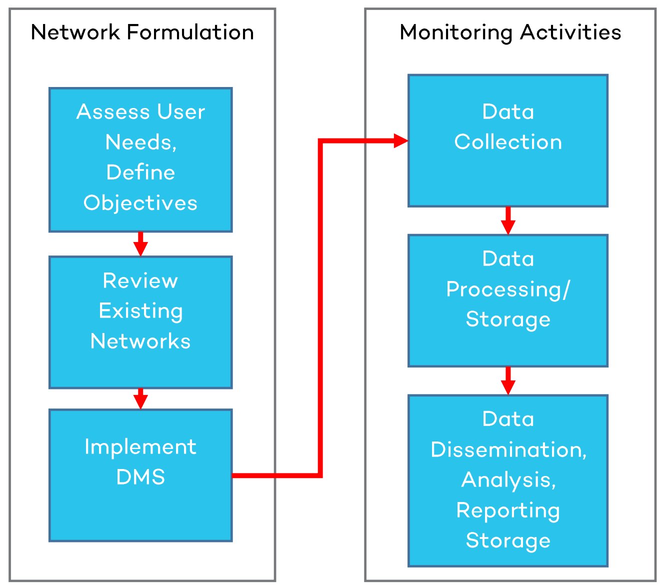

Figure 3. Flow chart of establishing and operating a monitoring network. Network formulation leads to ongoing monitoring activities.
Note: Periodically the network formulation is redone to ensure the monitoring effort is relevant to addressing the water resource issues.

Box 1. Steps in monitoring network design

There are many steps in developing the full HIS. The sequence of steps for developing a monitoring network, a subset of the full HIS development, include:

1. *Institutional review*: Review of mandates, roles and aims of the agencies involved in the implementing the HIS and those using the data to support decision making.
2. *Data need identification*: Collection of data should be done with the intention to address a water resource issue and to be used by water managers and interested stakeholders.
3. *Objectives of the network*: Prepare a set of objectives in terms of required network output based on the outcome need assessment from multiple parties.
4. *Prioritization*: A priority ranking among the set of objectives.
5. *Network density*: Based on the objectives, the required network density is determined, taking in view the spatial (and temporal) correlation structure of the variable(s).
6. *Review of existing network*: Reviewed are the existing network density versus the required one as worked out in the previous step; the spreading of the stations in conjunction with the hydro-meteorological, surface water and groundwater networks; the available equipment and its adequacy for collecting the required information; and the adequacy of operational procedures and possible improvements.
7. *Site and equipment selection*: If the existing network is inadequate to meet the information demands, additional sites as well as the appropriate equipment have to be selected.
8. *DMS selection*: Select the DMS to support the HIS network.
9. *Cost estimation*: Costs involved in developing, operating and maintaining the existing and new sites as well as the data centres must be estimated.
10. *Cost-effectiveness analysis*: Cost and effectiveness are to be compared. The last five steps have to be repeated in full or in part if the budget is insufficient to cover the anticipated costs.
11. *Implementation*: Once the network design is approved, the network is to be implemented in a planned manner, where execution of civil works, equipment procurement, and installation and staff recruitment and training are properly tuned to each other.

The monitoring network has to be reviewed after three years or at a shorter interval if new objectives need to be addressed. If revision is found necessary, the procedure should be re-executed.

Source: UNEP & WHO (1996)

3.2 Site and Instrumentation Selection Criteria

Based on identified objectives and needs, a general location is determined for a monitoring station. Following this, the actual sites for placement of the instrumentation must be selected. Baseline criteria to evaluate the sensor locations include physical consideration (exposure, aspect, slope, elevation, river morphology), site footprint, existing infrastructure/monitoring stations, vegetation, physical access, telemetry window (for telemetry systems), power source, security and land ownership. GIS information (e.g., aerial photographs, land-use maps, road maps) can be used to evaluate potential locations, followed by a field visit to confirm the location.

In addition to the site selection, instrument selection is required for each site. Common components for a recording gauge include the sensor, data logger, power source, cabling (between sensor and data logger) and infrastructure for mounting the system (World Bank, 2015). For telemetered systems, additional equipment at a site will include an antenna and a remote terminal unit (RTU). Though each type of equipment will have properties to consider when selecting instruments, common criteria for selecting instrumentation include:

- Sensor accuracy over the measurement range
- Construction of equipment (parts well made, waterproof)

- Reliability
- Ease of installation and use
- Cost including warrantees and maintenance agreements
- Energy consumption
- Compatibility among components
- Maintenance
- Familiarity (using like technology as much as possible)
- Product support (training, technical inquiries, repairs)

3.3 Telemerty

Real-time hydrologic monitoring systems are increasingly used in the decision-making process to provide up-to-date information for flood forecasting, water supply management, irrigation and hydro generation (Haeggli, 2009). Hydrometric observations coupled with real-time telemetry provide the basis for an objective analysis of water resources, allowing operators to consider numerous operating criteria and the impact of any decision, rapidly, efficiently and consistently. Real-time modernized data also eliminate human error and build trust among stakeholders, which aids in transparency in decision making. Thus, data may be used for resource management, engineering design, project operation or scientific investigations without the need for extensive checking, editing and correction.

Telemetric systems operate by sensors measuring parameters, a data logger storing readings and the RTU transmitting a data package containing the readings through an antenna (Figure 4) (Sauer, 2002). The data package is picked up by a receiver and passed on to a receiving station (a.k.a., hub station, monitoring centre), which decodes the transmitted data package and sends it to the data management system on a server where it can be processed, stored, analyzed and disseminated. Should the data not be received, systems with two-way communication can be programmed to prompt the field site to resend the data package. Receiver networks include land-, radio- and satellite-based networks.

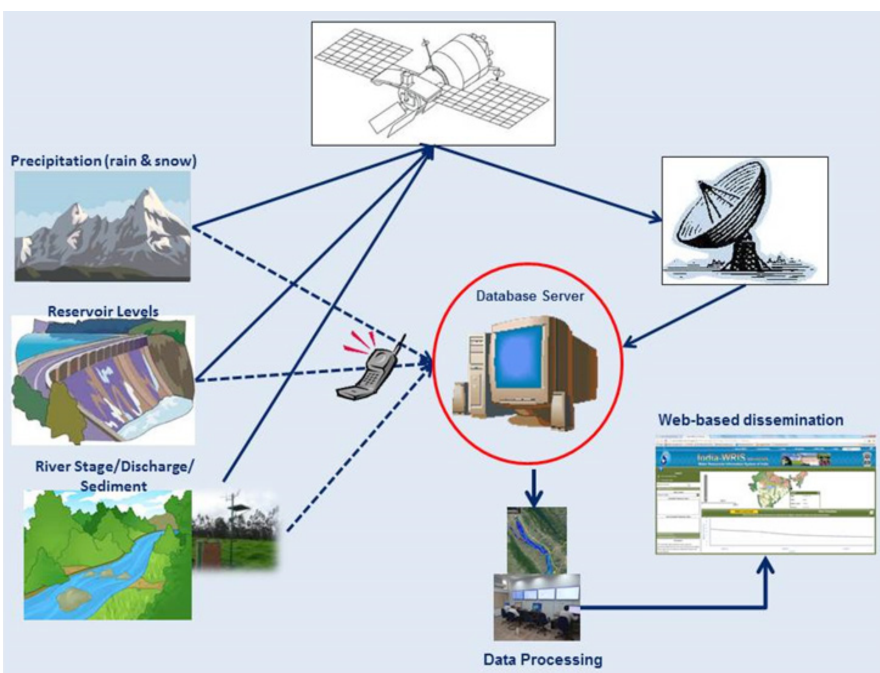

Figure 4. Schematic of a telemetered hydromet network.
Source: Hydrology Project (n.d.)

Table 2. Attributes of GSM/GPRS and VSAT telemetry systems.

TYPE OF COMMUNICATION	GSM/GPRS	VSAT
Range	Covered Network Area	No Limit
Power	Quite Low	High
Speed	Medium	Very High
Data Security	Low	High
Reliability	Low	High
Maintenance	Moderate	Unpredictable
Sabotage Malpractices	Quite Low	High
Price	Low	Very High
Running Cost	Low	High
Clearances from WPC	Not Required	Not Required
Error Detection	Good	Good
Need for ERS	No	Optional
Full-Duplex Capacity	Full Duplex	Full Duplex

Source: Haeggli (2009)

Types of telemetry systems include terrestrial-based (GSM/GPRS) and satellite-based systems (VSAT) (Table 2). In general, VSATs are used for networks required to be online during extreme events and thus are the preferred systems in flood warning systems. With the increased reliability comes increased cost in equipment, maintenance and provider service. GSM/GPRS relies on mobile phone networks, thus it is less expensive to equip and maintain, and easier to install. The limitation with GSM/GPRS is that its range is within the mobile network coverage and the reliability of the mobile network, which has a higher likelihood of failing during extreme meteorological events (Haeggli, 2009).

4.0 SURFACE WATER MONITORING SYSTEM

4.1 Overview

Surface water monitoring networks consist of a system of gauging stations that measure water levels and discharge rates. The network provides hydrologic data needed for the planning, design and management of conservation and utilization of the waters and other natural resources of the river system. Typical applications for a surface water monitoring network include water budgets, water allocation planning, climate variability (flooding, drought), infrastructure design, real-time warning systems, operations, reservoir management, resource management, risk analysis, policy design and evaluation, and scientific research. Surface water monitoring networks are also part of an integrated HIS including hydro-meteorological, geo-hydrological and water quality monitoring networks.

Through assessing data user needs, the identification of the monitoring objectives is the first consideration in the design of the surface water monitoring network. The second consideration in the design of the surface water monitoring network is the time and space of flow and the water level throughout the river/lake system. The monitored data should enable accurate estimation of the relevant characteristics of the hydrological regime of the river basin. Thus, the network requirement is greatly influenced by:

- Monitoring objectives, determined by the data needs of the hydrological data users
- Temporal and spatial variability of the river flow, determined by:
    - Climatic features like precipitation pattern in the catchment
    - Evapotranspiration
    - Physiographic features of the river basin, like size, slope, shape, soils, land use and drainage characteristics

These factors, along with the availability of financing, manpower and other resources, dictate the network design. It is recommended that, with limited resources, it is better to ensure fewer monitoring stations of higher quality as opposed to more low-quality monitoring stations (Haeggli, 2009).

4.2 Network Design

Surface water monitoring system design follows the overall design logic of overall HIS design and much begins with an understanding of the objectives. Depending on the objectives and setting, several types of monitoring networks can be considered based on the geographic size; geomorphology; and socioeconomic, ecologic and regulatory requirements within the area of interest. Baseline networks have at least one baseline station in each climatological and physiographic area. Station locations along main rivers should represent the majority of the discharge and locations with significant changes in the volume of discharge. Changes in volume include upstream of diversions or bifurcation and downstream of the confluence with tributaries. If a suitable location is not available below a confluence, the sites can be located above the confluence, preferably on the tributary. While establishing sites downstream of a confluence, care should be taken to ensure that no other small stream joins the main river. The drainage areas computed from origin up to consecutive monitoring stations on a large river should preferably differ by more than 10 per cent so that the difference in quantities of flow is significant (WMO, 1994). For reservoirs and lakes, water levels should be recorded as well as the outflow to rivers and canals.

Important in characterizing the surface water system is the discharge in tributary streams and rivers. While it is not financially feasible or practical with the available resources to monitor all the tributaries, a subset of “representative” streams and rivers have to be selected to estimate discharge in similar ungauged smaller water bodies. These data allow users to estimate flows in non-monitored tributaries of similar physiographic, vegetative and land-use character. If choosing between similar basins to place a monitoring station, the one with less human impact (more natural) should be chosen. Thus, great care is to be exercised in designing the network to ensure that all distinct hydrologic areas are adequately covered.

Coastal rivers need special consideration when developing the network due to backwater effects associated with tides and bifurcation of channels in deltas. In these regions, traditional stage-discharge relationships have limited application. Stage readings should be recorded with frequent discharge readings. For smaller rivers, use of an ADCP to continuously read discharge should be considered.

4.2.1 WMO Recommendations

The WMO provides a recommended minimum density of river network stations for flat, mountainous and arid regions (Table 3). As these recommendations are generalized, the final network density must ultimately be based on the network objectives, the temporal and spatial variability of river stages and flow, and the availability of finance, manpower and other resources.

Table 3. Minimum density of a hydrological network according to WMO (area in km^2 for one station). These should be considered rough guidelines.

TYPE OF REGION	RANGE OF NORMS FOR MINIMUM NETWORK	RANGE OF PROVISIONAL NORMS TOLERATED IN[1] DIFFICULT CONDITIONS
Flat regions	1,000 - 2,000	3,000 - 10,000
Mountainous regions	300 - 1,000[2]	1,000 - 5,000
Arid zones[3]	5,0002 - 20,000	------------------

Source: WMO (1994).

NOTES:
1. Last figure in the range should be tolerated only for exceptionally difficult conditions.
2. Under very difficult conditions this may be extended up to 10,000 km^2.
3. Great deserts are not included.

4.2.2 Use Of Existing Networks

Leveraging existing surface-water networks can provide a historical understanding of the timing and magnitude of discharge as well as identify gaps in the current network. Existing gauges should be considered in the new monitoring network; however, the location needs to be reevaluated given the updated objectives and cumulative knowledge of the hydrologic system. Each station must be reviewed to determine if it supplies necessary data for effective water management. There is reluctance for hydrologists and water resource planners to discontinue gauging stations, even though they might have fulfilled their intended objectives. In the design and evaluation of networks, it is essential that stations that no longer provide a significant benefit are shifted or discontinued. As monitoring network design is a dynamic process, networks have to be continually reviewed and updated so that they react to new priorities, changes in policies and fiscal changes.

Box 2. Prioritizing System

Following development of the "ideal" monitoring network, stations need to be prioritized by their objectives as well as financial and resource constraints. In prioritizing stations, the following questions should be asked (World Bank, 2015):

- What are the socioeconomic consequences of not collecting discharge/water level data at the site?
- What are the alternatives to establishing a discharge/ water level gauging station at the site under consideration?

Given these questions, a prioritization system is developed to determine stations to be culled from the "ideal" monitoring network. For example, stations might be prioritized as high, medium and low (World Bank, 2015). A station is considered "high priority" if it is a multi-purpose water resources development site, political boundary, upstream or downstream of major diversion(s), major ungauged basin and heavily polluted major water supply source. Characteristics of the "medium-priority" stations are medium-scale water resource development project sites, secondary basins and industrial development areas. Thus, "low-priority" stations would collect data on small projects or smaller tributaries that are not representative of surrounding basins or can be represented by another gauge. The appropriate prioritization criteria will need to be developed by the organizations implementing the monitoring network.

4.3 Monitoring Stations

The key components of characterizing the surface water system are measuring water levels and flows. Water level (stage) is measured directly as the water surface height above a datum (thalweg) or elevation. Water level can be measured using a staff gauge or continuously monitored using water level recorders to create a time series of the water level at the site.

For measuring water flows (*discharge*), the primary measurement is the stage. At most sampling sites, to compute discharge from stage, a series of concurrent stage and current meter readings (discharge measurements) are used to create a stage-discharge rating curve (Figure 5) (Rantz, 1982; United States Bureau of Reclamation, 2001). The curve is applied to the stage time series to compute a discharge time series. The shape, reliability and stability of the stage-discharge relationship are controlled by a section or reach of channel at, or downstream of, the gauging station. These “controls” can be natural or artificial (manmade for flow measurement purposes). Natural controls occur where a natural constriction or a downward break in channel slope occurs resulting from a rock outcrop or a local constriction in width caused by the construction of a bridge, friction by a channel bed or flow over a waterfall. To develop the stage-discharge relationship, multiple concurrent stage and discharge measurements are required over a range of discharges. If the riverbed is changing, the stage-discharge relationship will need to be periodically shifted to account for the new channel conditions.

Artificial controls have been designed to directly read the discharge from water level, thus eliminating the need for a large number of current meter readings. Reservoir spillways and control weirs frequently come into the “artificial” category. Periodic current meter readings over a range of discharges are still necessary to confirm the validity of the stage-discharge relationship. A good reference for developing and maintaining a stage-discharge rating curve is Standards for the *Analysis and Processing of Surface-Water Data and Information Using Electronic Methods: U.S. Geological Survey Water-Resources Investigations Report 01–4044* (Sauer, 2002).

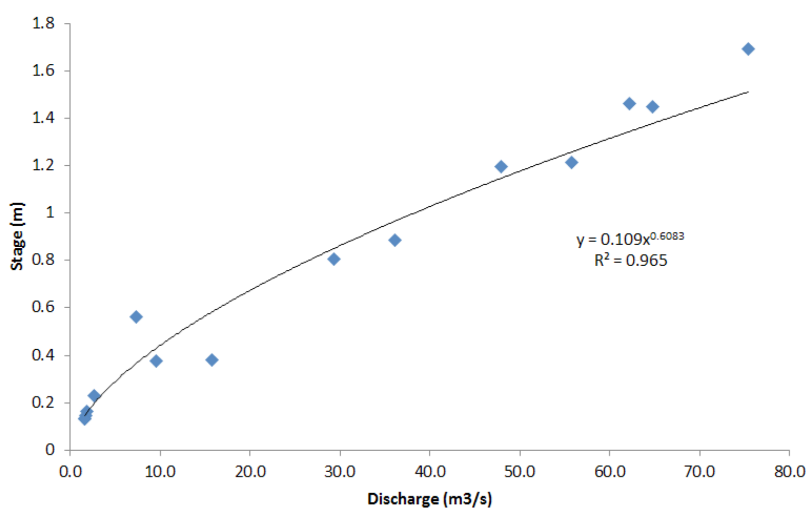

Figure 5. An example stage-discharge rating curve developed from concurrent stage and discharge measurements at a site collected throughout the year.

Note: characterizing the storage and flow of water (water quantity) is the foundation for understanding many aspects of water quality, as they determine the concentration, fate and transport of chemicals in water bodies.

4.3.1 Site Surveys

Following identification of the type and general location for a station, based on natural and artificial controls, the site selection process begins. Site selection usually involves a preliminary investigation in the office (review of maps, survey logs, historical records) followed by site visits to locations deemed most promising in the preliminary investigation. The final choice of site depends on the type and quality of the data required, the proposed sensor and accompanying equipment to be deployed, and logistics and budgetary constraints. The primary aspects that have to be considered include (WMO, 1994):

- Technical aspects: the hydraulic suitability of the site
- Logistical aspects: site accessibility, communication and staffing
- Security aspects: security of instruments, away from residential areas and playgrounds
- Legal aspects: land acquisition and rite of passage
- Financial aspects: including costs of land acquisition, civil works, equipment, data processing, and staffing and training

Water level sites should avoid high-turbulence zones and be in close proximity to stable and steep stream banks for installation of the instrument. The downstream control should be stable and sensitive to establish a stable stage-discharge relation, where significant changes in the discharge create significant changes in stage. For non-coastal stations, the site shall be outside the backwater influence of tidal zones, confluences and structures (e.g., reservoirs/lakes). The stage and current meter reading need not be at the exact location, but close enough so that no change in discharge is deemed to have taken place. Nearby benchmarks should be available or be established to allow regular survey of the gauge location.

4.4 Monitoring Duration

The frequency of hydrological measurements depends upon the monitoring objectives, desired accuracy, variability of data (hourly, daily, weekly, monthly, seasonally) and marginal cost-benefit of improved accuracy (WMO, 1994). In general, systems with high variability in the system will need short sampling frequencies. The variability can change during the year to reflect the changes in seasonality. Dry, warm seasons may be characterized by stable, low discharge conditions, while rainy seasons may be characterized by peak flow events, and thus the sampling frequency needs to reflect this variability. With increased sampling frequency comes increased cost in data storage equipment, processing and human resources. Therefore, costs will increase proportionally, and decisions have to be made regarding the benefits of the increased accuracy. That said, with the decrease in computer storage costs and adoption of real-time monitoring systems, the cost of increased monitoring has been greatly reduced. In addition, sampling frequency may change with changing monitoring objectives and increased knowledge of the hydrologic system.

4.5 Measurement Frequency

4.5.1 Stage Measurement Frequency

For stations with digital water level recorders, the standard frequency should be a maximum of an hourly rate. For flashy systems in response to precipitation events, particularly those in mountainous or in high-intensity rainfall areas, a frequency of 15 minutes may be required. In addition, where a river is heavily managed, levels may change comparatively quickly as a result of river regulation and abstraction that may occur a short distance upstream.

For manned stations with staff gauges only, hourly readings throughout a full day will apply during the rain seasons. During the dry season, two or three readings per day will be sufficient; with the provision that, in the event of unseasonal rainfall and river rise, the observations are intensified and extended over the full 24 hours. In some circumstances, one reading a day might suffice.

4.5.2 Current Meter Measurement Frequency

The required frequency of current meter measurement at a stage-discharge site depends primarily on the stability of the control section, as this will define how frequently gauge readings are required to achieve a given level of accuracy. The minimum number of gauge readings required to establish a good stage-discharge relationship for a stable, sensitive control is of the order of 10–12 over the full flow range. A precise interval between gauging readings cannot be specified, as the need to gauge may depend on the occurrence of flow in a particular range. Unstable channels and those affected by backwater or hysteresis resulting from unsteady flow will require more persistent and frequent measurement than stable controls. Recommended frequencies are proposed and summarized in Table 5.

If more than one condition exists at a station, then the condition requiring the most frequent gauging should be applied. For example, if a change in the control is detected at any station, or if current meter gauging suggests that the rating has shifted, then gauging should be intensified until the new rating is defined throughout the range. At sites with very unstable controls, it might be necessary to derive a new stage-discharge relationship for each season.

Table 5. Recommended observation frequency for current meter gauging

Station control	Frequency	Remarks
All stations (excluding structures) – initial calibration	Frequent gauging to capture data for as wide a range of events as possible.	10–12 should be considered the minimum over the low, medium and high flow ranges.
Stable natural channel	Monthly plus at least one high flow event a year	The monthly gauging can coincide routine DWLR downloading.
Backwater affected	Daily if backwater source not known Otherwise weekly	If an additional set of gauge posts are installed or an additional AWLR/DWLR, the changes in surface water slope can be estimated.
Unstable channels with silt, sand or gravel	During lower flow periods, daily or more frequent to obtain data for high events	
Unsteady flow with looped rating	Weekly	Assumes that rate of change from stage records of stage can be well enough defined.
Structures – initially	6 gauge readings over full modular measurement range to confirm calibration (performance) of structure, approx. 6 readings in the non-modular range.	Including 2 low flows. The modular limit should be defined.
Structures - after initial calibration (performance) check	1–2 gauge readings per year within modular range, 3–4 gauge readings a year in non-modular range	

Source: Hydrology Project (n.d.)

4.6 Instrumentation

4.6.1 Water Level Monitoring InstrumenTS

There are several common methods to measure water level (stage), each with advantages and disadvantages of measurement, cost, operation and maintenance (Table 6). Water level monitoring instruments include:

- **Staff gauges** – Manually read water level gauges, most commonly a vertical staff gauge. These are inexpensive, simple to install, intuitive and easy to understand. They do not provide a means of continuously recording water levels.
- **Shaft encoder** – Involves a float connected with a recorder that tracks changes in water

levels. The instrument is usually a float in a stilling well. Shaft encoders are best used on stable riverbeds where the channel does not change and there is little sedimentation. Instrumentation is inexpensive and never needs to be shipped to the manufacturer for calibration. However, initial shaft encoders require installation of a stilling well and maintenance through periodic flushing of the system.

- **Gas bubbler** – A tube is submerged and a gas is forced through at a known pressure. The pressure difference between the tube reading and atmospheric pressure is the depth of water. Water levels are recorded on a data logger. Gas bubblers are best used on open channels and reservoirs with stable riverbeds where the channel does not change, there is little sedimentation and there are no bridges or platforms nearby to install a radar system. An advantage is that the installation is relatively inexpensive. Disadvantages are the expense: the desiccant needs to be replaced periodically and they are not suitable for shifting channels with debris.

Table 6. Generalized attributes of water level recording instruments

DESCRIPTION	SHAFT ENCODER	BUBBLER	PRESSURE TRANSDUCER	ULTRASONIC	RADAR
Range	Large	Small	Medium	Medium	Large
Accuracy	Good	Good	Good	Good	Good
Tampering/Sabotage	High	High	Medium	Medium	Medium
Stilling Well	Essential	N/A	N/A	Preferable	Not essential
Installation	Simple	Difficult	Simple	Simple	Simple
Maintenance	High	High	None	None	None
Sediment effect	Medium	Very High	N/A	N/A	N/A
Cost	Medium	Large	Low	Medium	High

Source: Hydrology Project (n.d.)

- **Submersible pressure transducer** – Similar to the gas bubbler, this measures the hydrostatic pressure underwater. The difference between the pressure transducer reading and atmospheric pressure is the depth of water. Submersible pressure transducers are relatively easy to install and low cost. The disadvantage of pressure transducers is their vulnerability to debris, high water flows and water pollution, as well as the need for periodic factory calibration.
- **Ultrasonic/radar** – These sensors measure the water level by sending pulsed ultrasound or radar waves to the water surface and then measuring the time for the sound echo to return. Knowing the speed of sound, the sensor can determine the distance to the water surface. These sensors do not make contact with the water and thus are unaffected by the transparency, reflectivity, opacity or colour of the target. Ultrasonic sensors are less expensive and cover ranges of >10 m (sensor to water level). Radar sensors are more expensive, but cover a range of up to 30 m (sensor to water level) and can penetrate temperature and vapour layers that may cause problems.

4.6.2 Instrument Selection

Selection of the appropriate instrument will depend on the station purpose, presence of existing infrastructure (e.g., stilling well, bridge), distance to the water, desired accuracy, sedimentation rate, access and cost. Figure 6 presents the general logic for the preliminary selection of water level instrumentation based on setting (e.g., river, reservoir or canal), existing infrastructure and height above water. Generally, if a stilling well is present or to be constructed, a shaft encoder or ultrasonic level sensor are the options considered. For sites without a stilling well, but with an overhanging structure such as a dam or bridge, a downward-looking ultrasonic/radar is the primary option. If no pre-existing structures exist, then a bubbler or pressure transducer is considered.

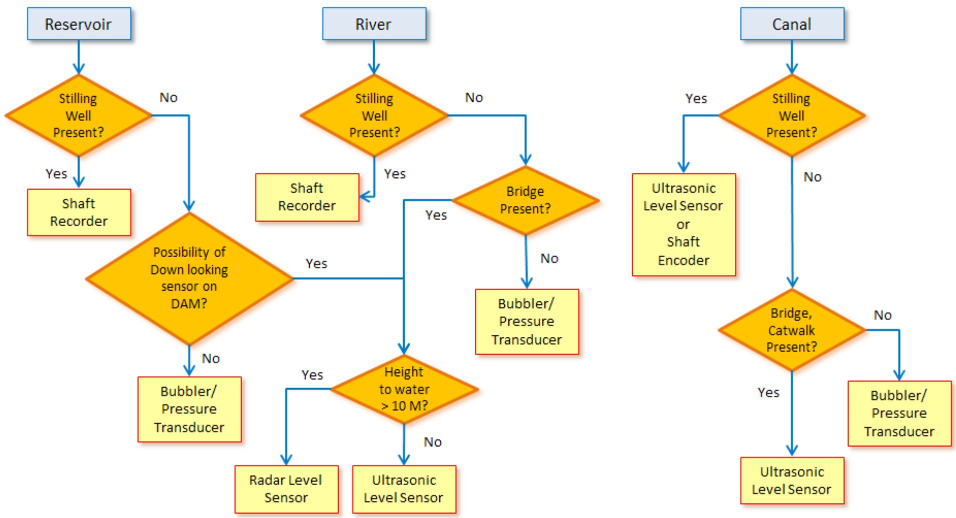

Figure 6. Logic for selecting water level measuring instrumentation for a station
Source: Hydrology Project (n.d.)

4.6.3 Discharge Measurement Instrumentation

Radar, acoustic Doppler current profilers (ADCP) and control structures are used for continuously measuring discharge in channels. Below is a brief description on each.

- **Radar** – Radar units are available that collect the surface velocity in addition to water level. Based on these measurements and the cross-sectional area, discharge can be calculated. This method works optimally in well-defined symmetric channels, such as canals, creeks and smaller rivers, where the radar velocity measurement represents the flow in the channel. For wide channels, more than one instrument along the cross section may be required. The advantages and disadvantages are the same, with radar applied for measuring surface water levels.
- **ADCP** – ADCPs use sonar to measure the current velocity by measuring the backscatter of sound waves off particles in the water column. The result is a velocity profile across a cross section that can be summed to compute discharge (Figure 7B). ADCPs are available as mobile and fixed units and are available to cover a variety of river sizes, including wadable (handheld AD velocimeter), medium rivers (pontoon [Figure 7A]) and larger river systems (attached to a boat). Mobile units are effective for gathering point measurements of discharge, which are necessary for developing the stage-discharge relationships. Fixed ADCPs that continuously monitor discharge are optimally suited for canals, estuaries, river deltas and river reaches that experience backwater to measure current, where currents change even though the water level stays the same. An increasing number of ADCPs are being installed in open channels to measure the discharge directly, thus removing the effort associated with obtaining the stage-discharge points. The primary disadvantage to ADCPs is that the units are expensive. As the units are in contact with the water, ADCPs are not a suitable solution for streams where debris such as logs and moving rocks can dislodge and possibly damage this expensive sensor.

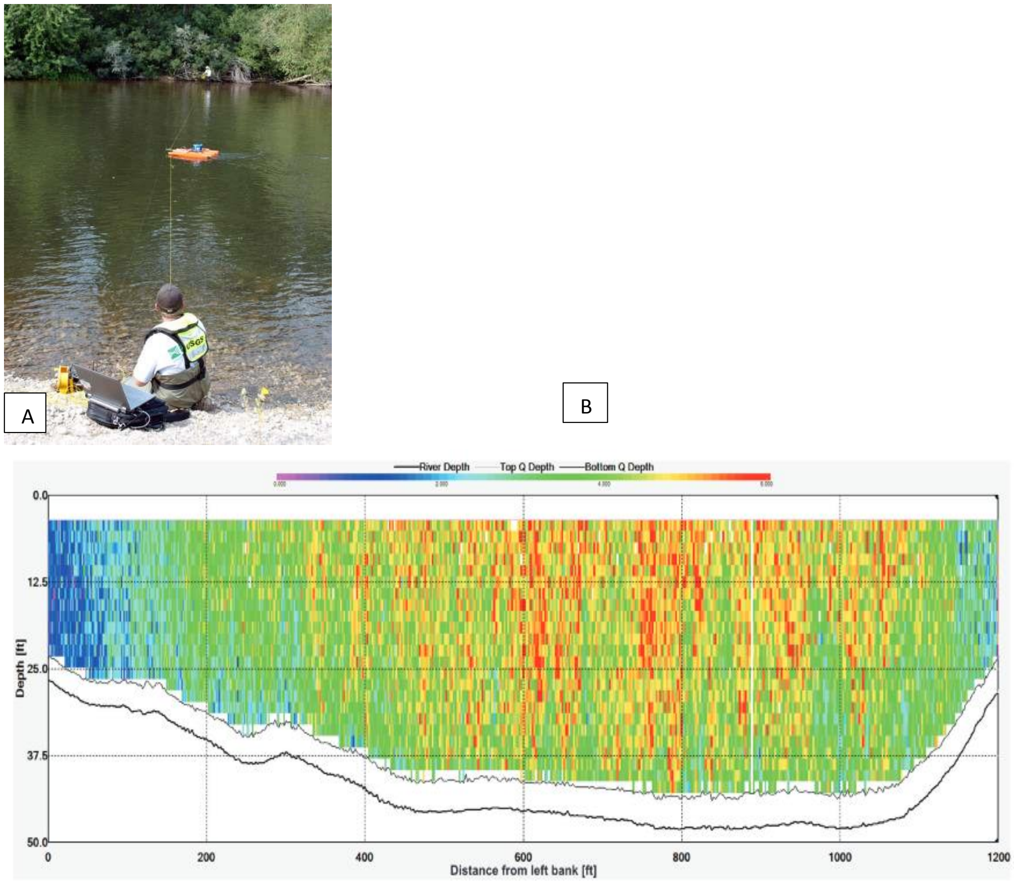

Figure 7. ADCP measuring discharge (A) (Photo courtesy of USGS) and an example of results (B) Typical ADCP output showing water depth and flow velocity profile for a river cross-section (Levesque & Oberg, 2012)

- **Control structures** – Control structures, such as calibrated weirs and flumes, have fixed cross sections where the stage-discharge relationship is known and constant. Coupling the control structure with a water level recorder provides a means of continuous recording discharge. The advantage is that periodic stage-discharge measurements are not required to build the relationship. The disadvantage is that the installation of the structures needs construction and maintenance.

4.6.4 Discharge Measurement

In addition to the water stage measurement described above, selection of the monitoring location is also important for obtaining a reliable *discharge* measurement. The type of instrument chosen for rivers, canals and reservoir gates is provided in Figure 8. For a stage-discharge station, both a stage measurement device and a current meter-gauging site are required in the same locality. However, it might not always be appropriate to locate the current meter-gauging site immediately adjacent to the stage measurement device, since some of their site selection criteria are different. Care should be taken to ensure that no inflow or outflow to the river or channel exists between the stage and discharge reading locations.

Box 3. Guidelines for selecting a discharge measurement

- The general course of the stream is straight for about 100 metres upstream and downstream from the gauge site.
- The total flow is confined to one channel at all stages and no flow bypasses the site as sub-surface flow.
- The stream bed is not subject to scour and fill and is free of aquatic growth.
- Banks are permanent, high enough to contain floods and free from brush.
- Unchanging natural controls are present in the form of a bedrock outcrop or other stable riffle during low flow.
- A channel constriction is present for high flow, or a fall or cascade that is unsubmerged at all stages to provide a stable relationship between stage and discharge. If no satisfactory natural low-water control exists, then installation of an artificial control should be considered.
- A site is available, just upstream of the control, for housing the data acquisition system where the potential for damage by water-borne debris is minimal during flood stages. The elevation of the data acquisition system should be above any flood likely to occur during the life of the station.
- The gauge site is far enough upstream from confluence with another stream from tidal effect to avoid any variable influences, which the other stream or the tide may have on the stage at the gauge site.
- A satisfactory reach for measuring discharge at all stages is available within reasonable proximity of the gauge site. It is not necessary that low and high flows be measured at the same stream cross section.
- The site is readily accessible for ease in the installation and operation of the gauging station. Facilities for telemetry or satellite relay can be made available, if required.
- If ice conditions might occur, it will still be possible to record stage and measure discharge.

Source: WMO (1994)

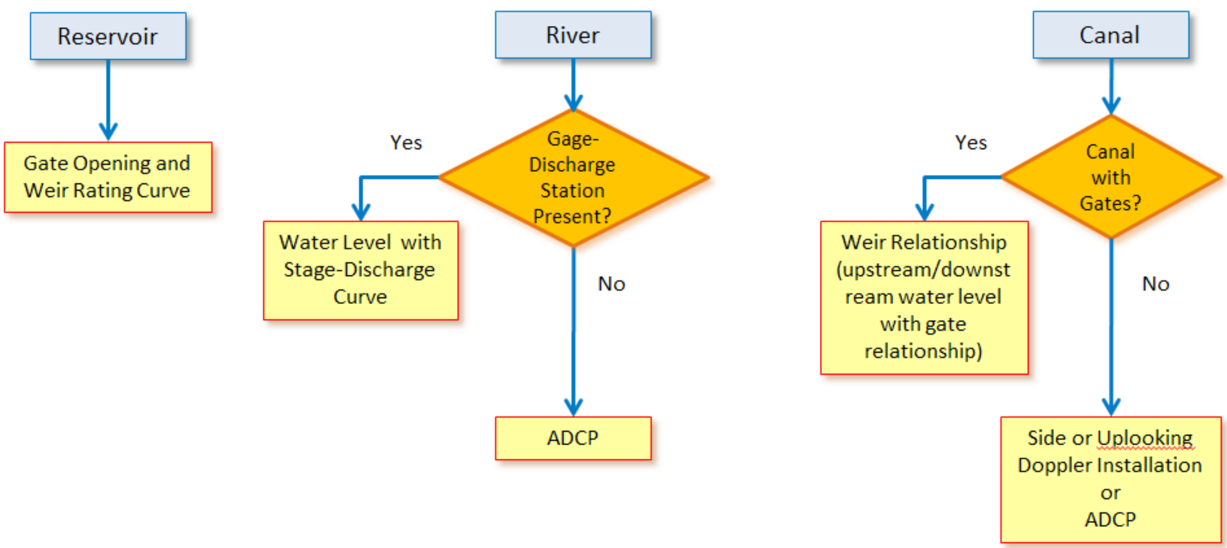

Figure 8. Logic for site selection of discharge measuring methods
Source: Hydrologic Project (n.d.)

4.7 Recommended Resources

http://pubs.usgs.gov/fs/2007/3099/

http://pubs.usgs.gov/wsp/wsp2175/

https://hydroacoustics.usgs.gov/

http://water.usgs.gov/hif/

http://water.usgs.gov/hif/programs/instrumenteval/HIFEvaluationGuidance.pdf

http://www.indiawrm.org/HIS.aspx

5.0 GROUNDWATER MONITORING SYSTEM

5.1 Overview

In addition to surface water systems, groundwater systems need to monitored and understood to know the full extent of available water resources for a region. A groundwater monitoring network is a system of dedicated groundwater monitoring wells in a geo-hydrological unit at which groundwater levels and water quality are measured (World Bank, 2015). Monitoring groundwater is performed to characterize groundwater quantity and quality in order to address issues regarding proper assessment and protection of groundwater resources. Types of water resource issues that groundwater data are used for include aquifer characterization (quality and quantity), water budgets, conjunctive management, safe yield of groundwater abstraction, salinity intrusions, water logging, water quality contamination characterization, aquifer recharge zone delineation, aquifer-recovery-storage (ARS) projects, policy design and evaluation, and research and studies.

The types of information collected in groundwater monitoring networks include the spatial and temporal distribution of water levels, water balance of an aquifer (recharge and abstraction) and hydraulic properties of the aquifer. Of particular interest is the long-term change of the groundwater levels and the seasonal periodicity. Given the water level record, hydrographs can be produced to indicate groundwater level as a response to changes in climate or management. Typical statistics include the magnitude of change, time lag to change, rate of change and duration of change. Thus, long-term groundwater monitoring is important in developing comprehensive and effective management plans.

5.2 General Design Considerations

Groundwater monitoring networks should reflect the hydrogeological system of the area under investigation as well as provide long-term records on the different aquifers being monitored. Many aquifer systems are vertically stratified and thus monitoring networks must observe water levels in shallow aquifers as well as deeper, multi-layer aquifers. In order to characterize the water budget for the aquifer, a minimum network should include a number of groundwater monitoring stations in the recharge area, runoff and discharge area for each of the aquifer systems. In addition to establishing a baseline monitoring system, the groundwater monitoring network must address the objectives identified by the user, which may add or transfer stations from previous monitoring locations. Ultimately, the groundwater network should support the management of supply for drinking water, irrigation, industrial/commercial, health and freshwater ecosystems.

The underlying lithology should be addressed when determining the depth of monitoring wells and density of stations. Aquifers comprised of clastic materials (e.g., sand or gravels) will have a different density than underlying geology comprised of fractured hard rock or limestone. The presence of major fault sections that can provide conduits for water movement also need to be considered. In general, the evaluation of the results is more difficult in hard rock formations as the underlying fractures, joints and faults that influence groundwater movement require additional information.

5.3 Network Design

The density of monitoring sites and instruments, observation wells and piezometers chosen for an observation well network will provide data representative of various topographic, geologic, climatic and land-use environments. Decisions about the areal distribution and depth of completion of piezometers should also include considerations about the physical boundaries and geologic complexity of aquifers under study. Water level monitoring programs for complex, multilayer aquifer systems may require measurements in nested piezometers (water level measuring devices) completed at multiple depths in different geologic units. If one of the purposes of a network is to monitor ambient ground-water conditions or the effects of natural, climate-induced hydrologic stresses, the observation network will require dedicated piezometers that are unaffected by pumping, irrigation and land uses that affect groundwater recharge.

As per earlier discussion, spatial density of groundwater monitoring networks can be classified into baseline, management and project types. Baseline networks extend over the entire major hydrogeological and groundwater development units under consideration, with observation sites representing typical hydrogeological characteristics in order to estimate the groundwater resource availability. The monitoring well of this network should remain monitored for a long period of time. Management networks supplement the baseline networks for estimating groundwater resources at a watershed scale and aquifer management. In management networks, the monitoring well's density is greater with distribution, to represent diverse hydrogeological units. The monitoring in this network should be continued for long periods with high frequency of monitoring. Project networks are for studying localized issues. The monitoring stations need to be operated for a limited period of time, ideally occurring before, during and after the project or study. Typical problem areas that a local network may have are for mining activities, industrial/commercial contamination, monitoring freshwater/salt water interface in coastal areas and evaluation of proposed abstraction schemes.

5.4 Monitoring Stations

Groundwater characterization is observed as water level in wells, discharge from springs and abstraction/recharge from pumping wells. Monitoring wells can be shallow wells, abandoned deeper tube wells and observation wells with single or nested piezometers (for characterizing multiple aquifer layers at a single location). For monitoring wells, knowledge of the geology across the screening interval (the depth range of the well casing permits water to enter the well) as well as proximity to abstracting wells needsto be considered.

Springs represent a location where the groundwater table (water level) intersects the ground surface. Care must be taken to determine if the spring is connected to a perched (shallow) or deeper aquifer system. Finally, when determining the abstraction rate from wells, it is rarely possible to monitor all pumping wells, so monitoring larger abstraction wells and representative wells is a solution. Wells are monitored either through a gauge attached to the pipes or through energy-use records in combination with pump capacity to estimate abstraction. In addition to the aforementioned considerations, network design and site selection criteria follow the same as those outlined in Section 3.

Monitoring duration and frequency are key considerations discussed in the following sections. Although often influenced by economic considerations, the monitoring duration and measurement frequency should be determined by the variability of water level fluctuations to fully characterize the hydrologic behaviour of the aquifer. Thus, the monitoring duration and frequency need to be able to pick up the periodic cycles (e.g., annual, seasonal, tidal cycles) from impacts due to other pressures (e.g., groundwater abstraction, recharge from land-use changes) and other long-term hydrologic changes (e.g., climate change). The monitoring objectives, financial and human resource constraints, and variability of hydrogeological conditions influence this monitoring duration and measurement frequency.

5.5 Monitoring Duration

Monitoring duration is a function of the monitoring objectives (Table 7). Short-term water level data is collected over periods of days, weeks or months during many types of groundwater investigations. Water level measurements needed to map the piezometric surface (a.k.a., water table) are generally collected within the shortest possible period of time (days or weeks) so that water levels represent a static hydrologic condition. Long-term data are fundamental to the resolution of many of the most complex problems dealing with groundwater availability and sustainability (Cunningham & Schalk 2011). Multiple years to decades are required to develop groundwater-level hydrographs needed to assess the effects of climate variability and of regional aquifer development or to obtain data sufficient for the development and use of analytical and numerical (computer) groundwater models.

Table 7. Monitoring duration as a function of the intended monitoring objectives.

INTENDED USE OF WATER LEVEL DATA	TYPICAL LENGTH OF DATA-COLLECTION EFFORT OR HYDROLOGIC RECORD REQUIRED			
	DAYS/WEEKS	MONTHS	YEARS	DECADES
To determine the hydraulic properties of aquifers (aquifer tests)	X			
Mapping the water table or potentiometric surface	X			
Monitoring short-term changes in groundwater recharge and storage	X	X	X	
Monitoring long-term changes in groundwater recharge and storage			X	X
Monitoring the effects of climatic variability			X	X
Monitoring regional effects of groundwater development			X	X
Statistical analysis of water level trends			X	X
Monitoring changes in groundwater flow directions	X	X	X	X
Monitoring groundwater and surface water interaction	X	X	X	X
Groundwater resource assessment			X	X
Numerical (computer) modelling of groundwater flow or contaminant transport	X	X	X	X

Source: Cunningham & Schalk (2011)

5.6 Measurement Frequency

Groundwater measurements are collected both through periodic monitoring and continuous monitoring. Periodic monitoring involves taking groundwater level measurements at weekly, fortnight, monthly or seasonal intervals. Periodic water level measurements are usually carried out through manual measurement techniques, such as chalked metal tapes or electronic water level indicators. Depending on the frequency and the hydrogeological conditions, periodic monitoring (e.g., quarterly, monthly) misses the hydraulic responses of aquifers to short-term stresses that occur between measurements.

Synoptic water level measurements are water levels in all the monitoring wells within a homogenous hydrogeological/drainage unit and are measured within a relatively short period (World Bank, 2015).

Synoptic water level measurements provide a "snapshot" of heads in an aquifer. Synoptic measurements should be taken when data is needed for mapping the altitude of the water table or potentiometric surface, determining hydraulic gradients, or defining the physical boundaries of an aquifer. Regional synoptic measurements made on an annual or multi-year basis should be used as part of long-term monitoring, to complement more frequent measurements made from a smaller number of wells.

Continuous monitoring uses digital water level recorders to measure water levels at a regular frequency. The continuous monitoring frequency (typically hourly, 6-hourly, daily) is set to capture water level fluctuations while efficiently collecting data. Hydrographs constructed from such measurements should be useful to accurately identify the effects of various stresses on the aquifer system and to provide the most accurate estimates of maximum and minimum water level fluctuations in aquifers. Continuous monitoring is used to characterize fluctuations in groundwater levels for groundwater resource assessment, as well as identify recharge zones and drought-prone areas, coastal zones, areas influenced by surface water sources (e.g., rivers, canals, irrigation) and waterlogged areas.

5.7 Instrumentation

Water level tapes – Electronic water level indicators and chalked steel tapes are manual devices used for measuring water level (Cunningham & Schalk, 2011). They are intuitive to use and inexpensive, but require manual operation and thus are only acceptable for periodic monitoring. Confirmation of water level using water level tapes should be performed during the pressure transducer installation to insure the instrument is correctly monitoring water level elevations.

Pressure transducers – Similar to the digital pressure transducers used for assessing surface water levels, submersible pressure transducers are used to record water levels in observation wells. Submergible pressure transducers measure the surface and submerged water pressures at the transducer sensors to compute the hydrostatic pressure. A transducer within the vicinity of the wellhead measures surface atmospheric pressure. Submersible pressure transducers are easy to install (just need to be lowered down the pipe) and are inexpensive. Many submersible pressure transducers come equipped with data loggers and can be easily connected to a telemetry system to relay data in real time. Given that real-time observations are not required for groundwater management, GSM/GPRS telemetry systems are adequate and thus many DWLRs on the market today have this functionality.

Figure 9. DWLR being deployed. *Photo courtesy of Global Water.*

5.8 Recommended Resources

Hudak P.F. & Loaiciga, H.A. (1993). An optimization method for monitoring network design in multilayered groundwater flow systems. *Water Resources Research, 29* (8), 2835–2845.

Prinos, S.T., Lietz, A.C. & Irvin, R.B. (2002). Design of a real-time ground-water level monitoring network and portrayal of hydrologic data in Southern Florida. United States Geological Survey, Water-Resources Investigations Report 01-4275.

Zhou Y. (1996). Sampling frequency for monitoring the actual state of groundwater systems. Journal of *Hydrology, 180*(1–4), 301–318.

Web

http://water.usgs.gov/ogw/networks.html

http://www.indiawrm.org/HIS.aspx

6.0 WATER QUALITY HIS

6.1 Overview

Along with surface water and groundwater *quantity*, monitoring water quality informs a comprehensive understanding of watershed systems and water resources for a region. A water quality monitoring network is a series of stations used to monitor the concentrations of chemicals (nutrients, trace metals, pesticides/herbicides, industrial organic micro-pollutants, oil and greases [UNEP & WHO, 1996]), bacteria, water temperature and the sediment load (mass of fragments). Assessing the water quality of groundwater and surface water helps water managers determine if water is acceptable for drinking, sanitation, health, commercial and industrial use, and agriculture and irrigation. It also supports the freshwater ecosystems upon which humans derive benefit. Typical water resource applications that use water quality data include water quality assessments; watershed management; drinking water and domestic, commercial, municipal and industrial (DCMI) use/effluent monitoring; nutrient runoff monitoring; ecological assessments; salinity intrusions mapping; infrastructure design; policy design and evaluation; and science and research.

Determining water quality requires the measurement and analysis of specific characteristics, including temperature, dissolved chemicals and bacteria. Water quality parameters that are typically determined through field-based monitoring include temperature, pH, dissolved oxygen, conductivity and turbidity. For other parameters, samples must be collected, then transported and analyzed in a laboratory, taking from days to weeks depending on the transport travel time and analytical methods. Monitoring values are compared with standards set by regulatory agencies to determine if the water is suitable for a particular use. Different activities require different levels of water quality (e.g., water quality for drinking and irrigation have different standards). Countries that do not have regulatory water quality standards often adopt standards developed by the U.S. Environmental Protection Agency and the World Health Organization. [1]

Fluvial sediment is defined as fragmental materials generally derived from weathered rocks that are transported in, suspended by or deposited from water. Fragments range in size from fine-grained colloidal silts to sands, gravels, cobbles and large boulders. These fragments are transported in suspension (suspended sediment) or by rolling, salting and sliding along the streambed (bedload sediment) (Figure 10). The total sediment load is the sum of suspended and bedload sediment loads. For monitoring sediment, the suspended load and bedload sediment are measured separately, then dried, sieved and weighed at a lab to get the total sediment load. If taken concurrently with a discharge measurement, the results from both can be combined to develop a sediment rating curve.

Sediment monitoring quantifies the suspended load and bedload sediment concentration in surface water systems. Quantifying sediment load helps water managers develop policies, design infrastructure and manage projects. Examples of monitoring sediment to address water resources issues include:

- Assessing water quality for human and ecological use
- Quantifying treatment cost for drinking and DCMI uses
- Determining reservoir siltation rates
- Designing infrastructure (e.g., bridge pier erosion and water intake siltation)
- Maintaining navigational channels
- Assessing channel stability and designing channel restoration efforts
- Developing land-use policies and best management practices
- Predicting and preventing mobilization of pollutants associated with sediment

[1] See the U.S. Environmental Protection Agency standards here: http://water.epa.gov/scitech/swguidance/standards/wqsregs.cfm; and the World Health Organization guidelines here: http://www.who.int/water_sanitation_health/dwq/guidelines/en/.

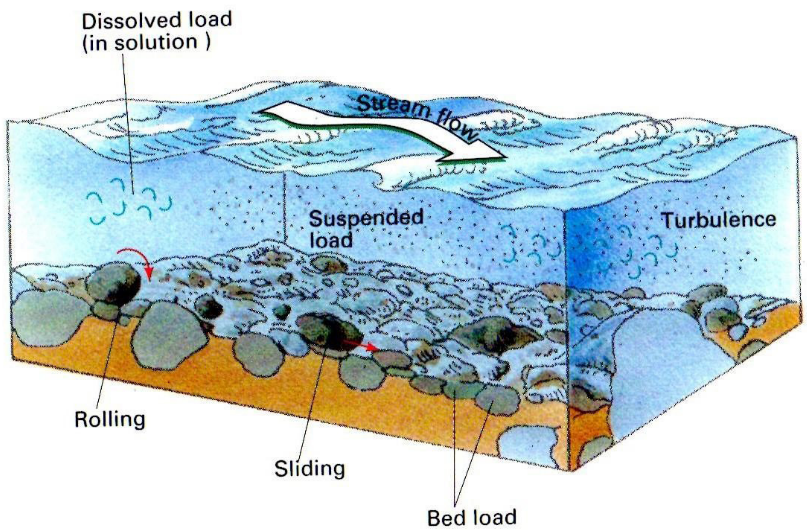

Figure 10. Schematic of the suspended and bedload transport methods is fluvial settings.
Source StudyBlue (2015)

Strategies for monitoring sediment will depend on factors such as general hydrology, land use, climate, vegetation, basin geology and type of water resource issue being addressed.

The UNEP & WHO (1996) W*ater Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes* is a comprehensive guide to developing water quality monitoring networks. Furthermore, the companion reference, *Water Quality Assessments. A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring, 2nd edition* (United Nations Educational, Science and Cultural Organization [UNESCO], WHO & UNEP, 1996), further specifies how water quality monitoring can be used in the water quality assessment process. Much of the information for this chapter is gleaned from these documents. Though an effective means of assessing water quality impacts on ecosystems, this chapter does not discuss sampling aquatic species for estimating pollution in natural waterways.

6.2 General Considerations

Water quality is influenced by natural factors and anthropogenic (human) influences (UNEP & WHO, 1996), both of which must be considered when establishing and interpreting data from a water quality monitoring network. Natural factors include the geological, topographical, meteorological, hydrological and biological systems active in the drainage basin. Water quality conditions can vary from diurnally to seasonally to annually due to differences in runoff volumes, weather conditions and water levels. Anthropogenic polluting activities include discharges of domestic, industrial, urban and other wastewaters into the watercourse (point source), and the spreading of chemicals on agricultural land (diffuse) in the drainage basin (Table 8). Point source can be monitored at discrete locations (e.g., outfalls to major rivers) to determine the loading from the source. Typical sources include sewage treatment, industrial waste effluent, solid waste disposal, animal feedlots and mine-adit runoff, and processing plant effluent. Diffuse (a.k.a., non-point) sources arise from many small inputs over a wide area and are difficult to monitor. Examples include unsewered fecal pollution and agricultural land runoff. Runoff from waste piles and tailing ponds can also be diffuse in its delivery to local water bodies.

Table 8. Sources and significance of pollutants resulting from human activities (UNEP & WHO, 1996). Note: "x" denotes low local significance, "xx" denotes moderate or regional significance, "xxx" denotes high local or regional significance and "G" denotes global significance.

SOURCES	BACTERIA	NUTRIENTS	TRACE METALS	PESTICIDES AND HERBICIDES	INDUSTRIAL ORGANIC MICRO- POLLUTANTS	OILS AND GREASES
Point Sources						
Urban sewage	xxx	xxx	xxx	x	xxx	
Industrial effluent		x	xxxG	x	xxxG	xx
Diffuse Source						
Agriculture	xx	xxx	x	xxxG		
Urban waste and runoff	xx	xx	xxx	xx	xx	x
Industrial waste disposal		x	xxx	x	xxx	x
Dredging		x	xxx	x	xxx	x
Navigation/harbours	x	x	xx		x	xxx
Internal Recycling		xxx	xx	x	x	

Developing a water quality and sediment monitoring network follows the same procedures as groundwater and surface water sampling (Section 3). As with groundwater and surface water monitoring networks, the first step is identifying the purpose of the monitoring, as this will determine the constituents of concern (CoCs) to be monitored. Table 9 provides a list of the typical CoCs monitored in a baseline network. Other constituents that are typically collected in water quality sampling include biological oxygen demand (BOD), pesticides, and metals (e.g., copper, iron, mercury). Following the CoC selection, consideration must be taken into account for the natural system (climate, physiographic conditions, geology, freshwater ecosystems) as well as the point and diffuse sources of pollution. Station locations should be considered where surface and ground monitoring occurs, as well as near structures such as bridges where sampling occurs during a variety of flow conditions.

Table 9. Variables used in the GEMS/WATER program for basic monitoring (UNEP & WHO, 1996)

MEASURED VARIABLES	STREAMS: BASELINE AND TREND	HEADWATER LAKES: BASELINE AND TREND	GROUNDWATER: TREND ONLY
Water discharge/level	x	x	x
Total suspended solids	x		x
Transparency		x	
Temperature	x	x	x
pH	x	x	x
Electrical conductivity	x	x	x
Dissolved oxygen (DO)	x	x	x
Calcium	x	x	x
Magnesium	x	x	x
Sodium	x	x	x
Potassium	x	x	x
Chloride	x	x	x
Sulfate	x	x	x

MEASURED VARIABLES	STREAMS: BASELINE AND TREND	HEADWATER LAKES: BASELINE AND TREND	GROUNDWATER: TREND ONLY
Alkalinity	x	x	x
Nitrate	x	x	x
Nitrite	x	x	x
Ammonia	x	x	x
Total phosphorus (unfiltered)	x	x	
Phosphorus, dissolved	x	x	
Silica, reactive	x	x	
Chlorophyll a	x	x	
Fluoride			x
Fecal coliforms (trend stations only)	x	x	x

Sediment sampling must consider the primary source of transport (suspended load, bedload or total load) that needs to be characterized for the issue being addressed. For example, stability for bridge piers may be primarily concerned with bedload transport, whereas intake for a water treatment plant may be primarily concerned with the suspended sediment load. In addition to the issues being addressed, factors to consider are climate, hydrologic system, geology, river morphology, riverbed particle size distribution, upstream land use, and downstream ecological and anthropogenic uses. A good reference for sampling procedures is *Field Methods for Measurement of Fluvial Sediment* (Edwards & Glysson, 1979).

6.3 Network Design

For general characterization and monitoring of water quality conditions, the network should include baseline stations, stations downstream/downgradient of major potential pollution and stations upstream/upgradient of major uses of water. Given the monitoring objectives, the density will follow the general rules associated with baseline, management and project networks described in Section 2. For example, to monitor the impacts associated with agriculture in a watershed, a groundwater and surface water monitoring network was established in the catchment in Figure 9. Water quality samples are collected upstream, within and downstream of the fields. Upstream is considered both the irrigation surface supplied to the fields as well as the upgradient groundwater. For two of irrigated areas, small communities located upgradient are a potential source of groundwater pollution entering the fields, and thus monitoring wells are placed upstream of the irrigated areas to characterize the subsurface inflow. Within and downgradient of the fields, the groundwater is sampled to determine the impact of irrigation on groundwater. Effluent running in agricultural drains from the fields is monitored for surface water monitoring and to prove compliance with governmental regulations. Finally, water quality is monitored in a series of locations along the major river to characterize water quality degradation that may occur with diffuse pollution sources.

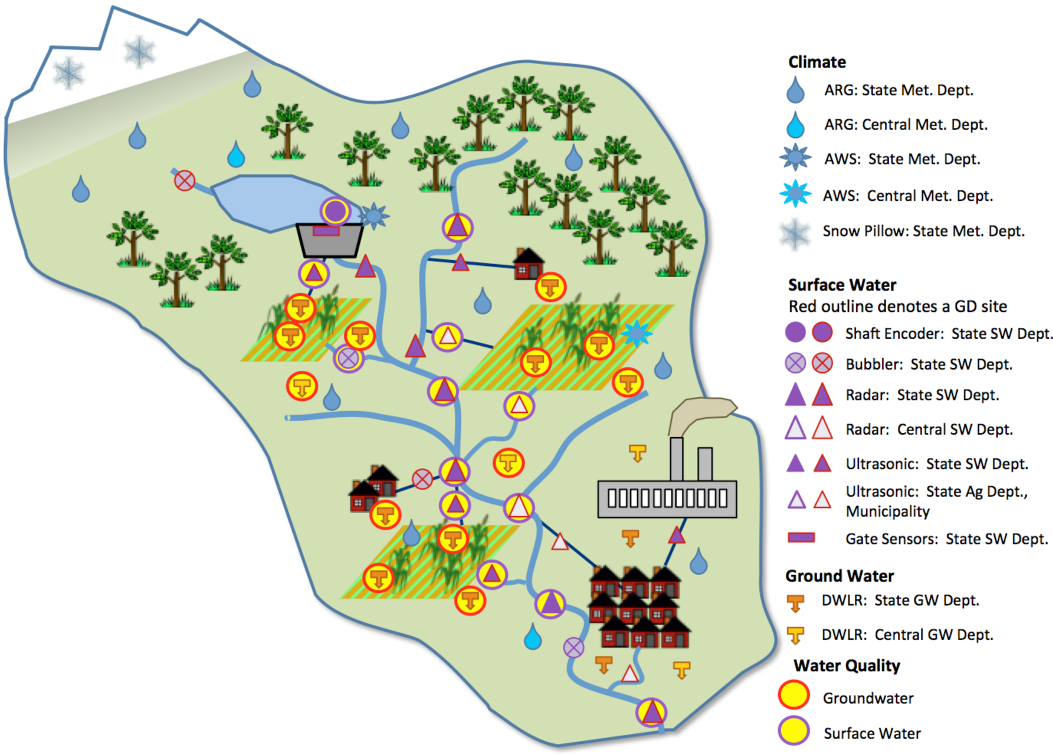

Figure 11. Example basin with a water quality HIS Networks to characterize the water quality impacts of agricultural. ARG is an automatic rain gauge; AWS is an automatic weather station; and DWLR is a digital water level recorder.

For project-level monitoring, the network has to include upstream (upgradient for groundwater), on-site and downstream (downgradient for groundwater) sampling locations. Upstream sampling locations are crucial for characterizing groundwater and surface water entering the baseline water quality condition that, when compared with downstream sampling locations, determine the project's influence on water quality conditions. Upstream sampling can limit the risk of a project being attributed with degrading water quality conditions that are associated with upstream pollution sources. Onsite sampling is important to characterize the movement of a chemical within the project site, to ensure the health and safety of staff, and it can be used to identify cost-saving measures. Downstream water quality monitoring of effluent and drains is important in characterizing downstream pollution loading, evaluating if water quality treatment facilities are properly functioning, and to be in compliance with regulatory requirements.

In regards to sediment monitoring, the need for sediment data is usually tied to specific site-related issues. Addressing these kinds of issues requires an understanding of the sediment transport characteristics of the specific river reach in question. For this reason, network density is not an especially useful metric when it comes to sediment monitoring; rather, each location where sediment transport is of concern will require a site-specific monitoring strategy. For site selection, the following criteria should be observed (World Bank, 2015).

1. Stream gauge to provide water discharge records
2. Single channel with minimal overbank
3. Significantly downstream to have mixing from tributaries or point sources of sediment or CoCs
4. Accessible during all weather conditions

5. Larger rivers, ideally a bridge from which to sample. Otherwise, the site needs to be boat-accessible over a wide range of flow conditions.
6. Power source, electrical line or solar
7. Secure site to avoid vandalism or theft of equipment
8. Installation approved by property owners
9. If real time is used, telemetric connection

6.4 Monitoring Duration

Like water quantity, water-quality monitoring can be baseline, management or project with respect to monitoring duration. Baseline networks, meant to capture water quality trend analysis over a large basin or aquifer, require a long-term monitoring program. Conversely, project networks address site-specific issues, and thus are shorter in duration and are targeted in their collection effort. For the latter, ideally the monitoring occurs before, during and after the project activities. If the project has polluted the project area or surrounding environment, then monitoring may continue for years or decades following cessation of the activities.

6.5 Measuring Frequency

Water quality sampling frequency depends upon the objectives of the sampling program and the water body of interest (UNEP & WHO, 1996). Aquifers respond slowly to water-quality inputs; therefore, collecting discrete samples on a monthly or seasonal sampling frequency is adequate. Rivers are subject to rapidly changing flows due to rain or snowmelt, which in turn can have a dramatic effect on water-quality parameters in a matter of days, hours or even minutes. Biological and chemical parameters often exhibit diurnal responses related to sunlight, photosynthesis and respiration. To understand these processes, initial detailed monitoring is required (UNEP & WHO, 1996). Continuous monitoring is often an effective means of understanding the processes. Once the processes are understood, the sampling frequency can be adjusted. An example of the frequency for streams, lakes, rivers and groundwater water quality sampling is presented in Table 10.

Table 10. Recommended sampling frequency for GEMS/WATER stations.

Baseline stations		
Streams	Minimum:	4 per year, including high- and low-water stages
	Optimum:	24 per year (every second week); weekly for total suspended solids
Headwater lakes	Minimum:	1 per year at turnover; sampling at lake outlet
	Optimum:	1 per year at turnover, plus 1 vertical profile at end of stratification season
Trend stations		
Rivers	Minimum:	12 per year for large drainage areas, approximately 100,000 km^2
	Maximum:	24 per year for small drainage areas, approximately 10,000 km^2
Lakes/reservoirs	For issues other than eutrophication:	
	Minimum:	1 per year at turnover
	Maximum:	2 per year at turnover, 1 at maximum thermal stratification
	For eutrophication:	
	12 per year, including twice monthly during the summer	
Groundwaters	Minimum:	1 per year for large, stable aquifers
	Maximum:	4 per year for small, alluvial aquifers
	Karst aquifers:	same as rivers

Source: UNEP & WHO (1996)

For sediment, the initial effort includes sampling the sediment discharge over a wide range of discharge conditions. Once adequate data has been obtained to characterize sediment transport, a discharge-sediment or turbidity-sediment rating curve is computed. The rating curve is then applied to the continuously monitored discharge or turbidity time series record to estimate sediment load. Following initial calibration, the site should periodically be sampled to confirm the validity of the rating curve.

6.6 Grab Versus Integrated Samples

Ideally, the water quality sample collected at a site will be representative of water quality at that location. Therefore, care needs to taken in determining if a single "grab" sample is sufficient, or whether an integrated sample collection is required. For a grab sample to be sufficient, vertical and lateral mixing of the CoCs need to be complete throughout the water body. In riverine conditions, the sampling location must be considered in relation to point sources of pollution. Pollution contribution into a river may require several kilometers for the source water to be fully mixed across the river channel (Table 11) (UNEP & WHO, 1996). To verify that a sampling site represents mixed conditions, 3–5 samples along a cross section taken at multiple depths are collected and compared during the preliminary sampling for the site (UNEP & WHO, 1996). If the samples measure different concentrations of CoCs, then multiple samples or an integrated sampler will need to be employed when monitoring at the site. Evaluation should be conducted at multiple flow conditions to verify that the mixing conditions are consistent for various discharges.

Table 11. Average downstream distance for full mixing from point source.

AVERAGE WIDTH (M)	MEAN DEPTH (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

Source: UNEP & WHO (1996)

Evaluating lakes can be more complex, as multiple sources feeding the lake may be present. Furthermore, thermal stratification, wind, salinity levels and bathymetry (e.g., narrow bays) all influence the mixing in the lake. Therefore, preliminary sampling to determine the proper sampling locations in the lake is required for optimum monitoring of water quality. For example, a stream leading into a narrow bay may have limited mixing in the main body of the lake and thus would need to be monitored separately. Lakes greater than 10 m in depth can develop a thermocline (> 3°C vertical difference in temperature), which may cause different water quality conditions above and below the change in temperature. In sampling a location with a thermocline, the minimum vertical density of samples is 1 m under the surface, just above and below the thermocline, and 1 m up from the lakebed (UNEP & WHO, 1996).

6.7 Measuring Instruments

6.7.1 Chemistry

Aside from the parameters measured at the site (pH, temperature, conductivity and DO), the sample container, preservatives and refrigeration will depend on the CoC and laboratory method used to evaluate the sample. Collection of the sample can be either point measurements (grab sample) or lateral and depth integrated sample. For shallow water bodies, the sample should be collected from approximately 20–30 cm below the water surface with care not to minimize collecting floating material or bed material into the container. If the water is less than 40 cm, the sample should be collected at half of the actual water depth. For deeper grab samples, instruments are available that can be lowered to sample at a prescribed depth. Following sample collection, on-site field parameters need to be measured and water samples packaged for transport to a laboratory. In general, the samples should be kept close to 4°C, in the dark as much as possible and transferred to a laboratory as soon as possible. Samples can be kept cold in insulated coolers containing either ice or ice packs. If not possible for all samples, CoCs that can volatilize (e.g., BOD, coliforms, chlorophyll, pesticides and other organics) MUST be kept at 4°C in the dark. Samples to be analyzed for the presence of metals should be acidified to below a pH of 2 with concentrated nitric acid and can be kept up to six months before being analyzed. Mercury determinations should be carried out within five weeks. Examples of sampling containers and pre-treatment are presented in Table 12. For integrated samples over the water column, a variety of samplers are available, depending on the depth that is being sampled. These can be deployed by hand, from a bridge or off a boat (Figure 12). The logic for selecting the depth integrated water quality samplers is presented in Figure 13.

Figure 12. Deployment of the US DH-95 sampler.
Photo courtesy of USGS

Table 12. Example of sampling containers and pre-treatment for water quality parameters.

PARAMETER GROUP	PARAMETER	SAMPLE CONTAINER	SAMPLE PRE-TREATMENT
General	Temperature	On-site analysis	On-site analysis
	Turbidity/suspended solids	1	On-site analysis/None
	Conductivity	On-site analysis	On-site analysis
	pH	On-site analysis	On-site analysis
	Dissolved oxygen	2	7
	Dissolved solids	1	None
Nutrients	Ammoniacal nitrogen	3	8
	Total oxidized nitrogen	3	8
	Total phosphorus	4	None
Organic matter	Chemical oxygen demand	3	8
	Biochemical oxygen demand	2	4°C, Dark
Major ions	Sodium	3	None
	Potassium	3	None
	Calcium	3	None
	Magnesium	3	None
	Carbonates and bicarbonates	1	None
	Chloride	1	None
	Sulfate	1	None
Other inorganics	Silica	1	None
	Fluoride	1	None
	Boron	1	None
Metals	Cadmium	3	9
	Mercury	4	9
	Zinc	3	9
Organics	Pesticide (Indicator)	5	4°C, Dark
	Synthetic detergents	1	None
	Organic solvents	1	4°C, Dark
	Phenols	5	8
Microbiological	Total coliforms	6	4°C, Dark
Biological	Chlorophyll 'a'	1	4°C, Dark

Source: UNEP & WHO (1996). Note: as the sampling containers and pre-treatment requirements pertain to the methods presented UNEP & WHO (1996) report, it is recommended to confer with the laboratory on the analysis method requirements for the parameters in the users study.

NOTES:
Containers:
1. 1000 millilitre polyethylene bottle
2. Special BOD bottle (normally 300 millilitre)
3. 500 millilitre polyethylene bottle
4. 100 millilitre glass bottle
5. 1,000 millilitre glass (or Teflon) bottle with Teflon lined caps
6. Strong thick-walled, screw-capped glass bottle (300 millilitre capacity). Only good quality will maintain a good seal after multiple sterilizations in an autoclave.
Preservation:
7. Samples for dissolved oxygen analysis are fixed by adding 1 ml of manganous sulfate solution, 1 ml of alkaline iodide-azide solution and 1 ml of concentrated sulfuric acid to the sample and mixing. Care should be taken to ensure that no air is added to the sample during this process.
8. Samples should be acidified with 2 ml of concentrated sulfuric acid.
9. Samples should be acidified with 2 ml of concentrated nitric acid.

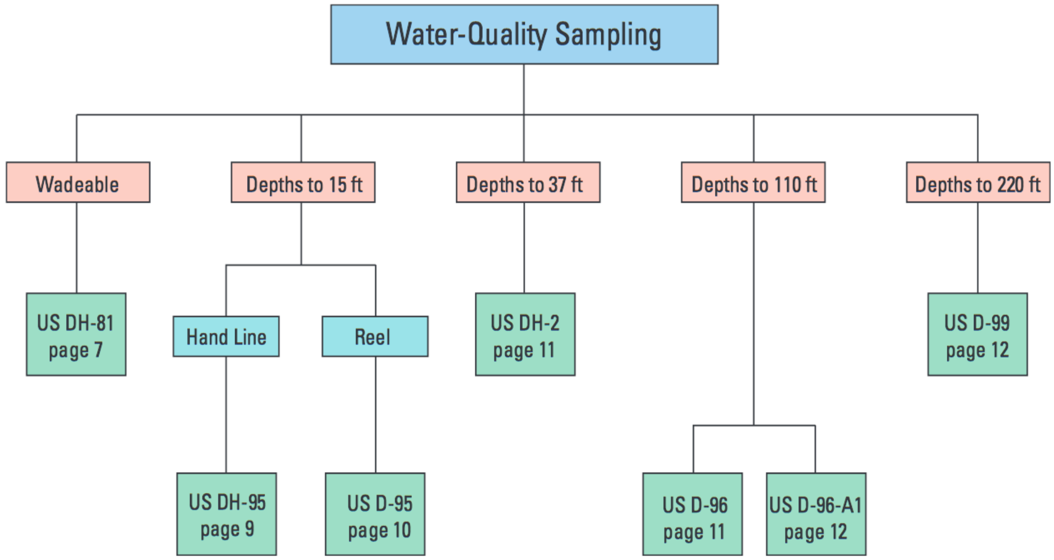

Figure 13. Selection logic for determining depth integrated water quality sampling equipment.
Source: Davis (2005).

Figure 14. Multi-parameter water-quality sonde with temperature, DO, conductivity, pH and turbidity sensors.
Photo courtesy of Azo Materials.

Sensors exist that allow for the continuous monitoring of several common field parameters, including water temperature, conductivity, pH, dissolved oxygen and turbidity. These sensors are available individually or bundled together into a multi-parameter sonde with several sensors attached in a single unit (Figure 14). For installation, structure is required that is available for mounting the instrument such that the sampling location is representative of the water quality at the site. One disadvantage of these instruments is that they are in contact with the water, thus are subject to damage from debris or pollution.

6.7.2 Sediment

Sediment-measuring devices include suspended and bedload sediment samplers for point measurements. For continuous monitoring of the suspended sediment load, turbidity meters and ADCPs are employed.

Suspended sediment samplers are lowered through the water column to collect the suspended sediment in a container. To achieve the full profile of the river, this is typically performed at 10 or more locations across the river. Once completed, the sample is then dried, sieved and weighed in a lab to determine the suspended load. Suspended sediment samplers

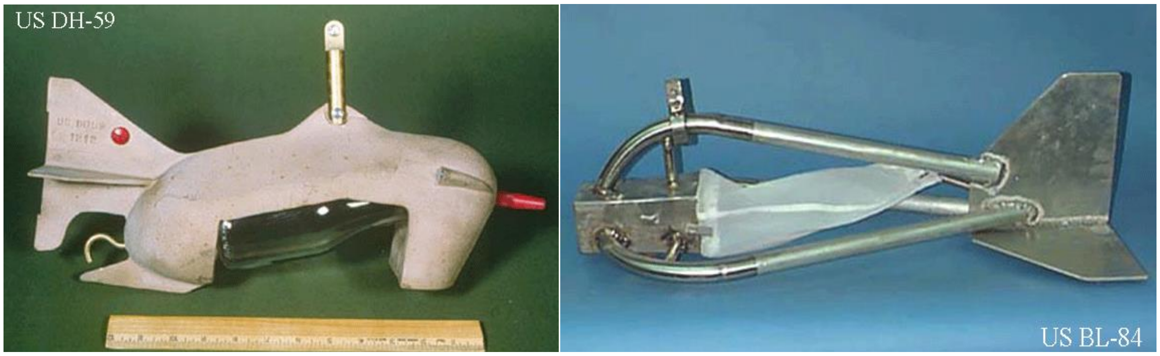

Figure 15. DH-59 Depth-integrating suspended sediment sampler (left) and a BL-84 bedload sediment sampler (right)
Photos courtesy of USGS

are available in a variety of different models that must be matched to field conditions (depths and velocities) to achieve quality sediment data (Figure 14). Davis (2005) outlines the selection criteria in a flow chart (Figure 15).

Bedload sediment samplers: Bedload is measured using a Helley-Smith Bedload Sampler, a device placed on the riverbed with a 3 x 3 inch opening to collect material moving along the bottom (Figure 15). The bedload sample is collected in a 0.25 mm mesh bag on the sampler, then dried and weighed in a lab to determine the bedload. Handheld and suspended versions of the sampler are available for smaller and larger rivers, respectively. Helley-Smith Bedload Samplers with 6 x 6 inch orifices are also available for rivers with coarse sediment. Bedload samples are often sieved to determine the particle size distribution of the bedload.

Turbidity sensors measure water clarity by shining a light into a small sample of water and measuring the amount of light refracted off particles in the water. Turbidity sensors can either be deployed as a

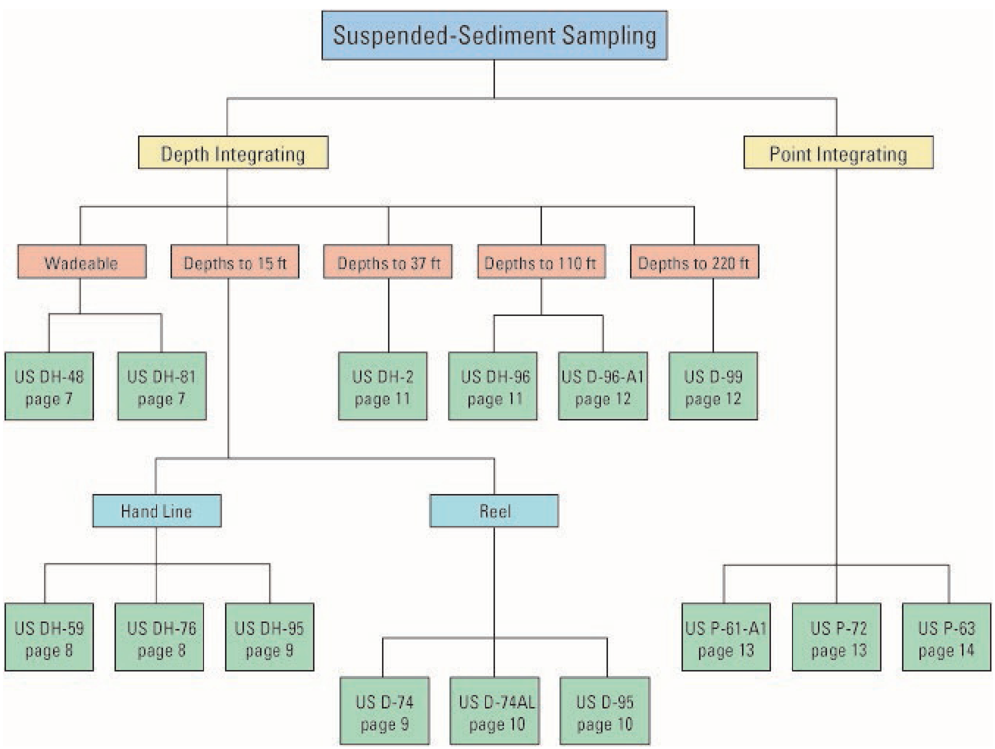

Figure 16. Selection logic for determining suspended-sediment sampling equipment in fluvial systems.
Source: Davis (2005).

single sensor or included as one of several sensors on a multi-parameter water-quality instrument. One disadvantage of turbidity sensors is that they only measure turbidity at a single location, which may not be representative of the cross-sectional average. To develop an accurate time series of the suspended load, a rating curve should be developed by taking simultaneous suspended sediment samples and turbidity sensor readings. The rating curve is then applied to the continuous readings from the turbidity sensor to develop a time series of the suspended sediment load.

ADCPs have been used to monitor suspended sediment concentration in rivers by correlating acoustic backscatter signal strength off particles with sediment concentration. The change in frequency of the return or "backscatter" signal is measured and used to determine the velocity of the particle. From that, the velocity of the water is inferred. The advantage to ADCPs is the partitioning of the acoustic signal into multiple cells across the channel, thereby providing a representation of the cross-sectional variation in sediment concentration. The disadvantages are the cost of the instrument and that the sensor is in contact with the water and susceptible to damage by debris or pollution.

7.0 HIS FOR MONITORING METAL MINING ACTIVITIES

7.1 Overview

Mining has the potential to affect the quantity and quality of surface water and groundwater resources. Impacts on aquatic life can include increased mortality, health or reproductive problems, and a reduction in the number of species present (Fraser Institute, 2012). Impacts on human health can occur where the quality of water supplies used for irrigation, drinking and/or industrial applications are affected. These impacts to natural and anthropogenic uses of water can increase insecurity in water and related systems, such as food and energy systems, upon which local communities rely. Thus, monitoring water quantity and quality before, during and after mining activities is crucial to assessing and, if required, mitigating the negative effects of mining.

The uses of an HIS to monitor and manage mining activities are numerous. HIS can be used for developing environmental and water management plans; providing data for planning and designing the mine and supporting infrastructure; identifying sources of mine-related pollution to initiate prevention and mitigation; complying with legal requirements; supporting audits of the monitoring to comply with effectiveness standards (e.g., ISO 14001); providing data for analysis and/or numerical modelling; limiting the risk for legal actions against the mine; and assuring shareholders that the mine is operating conscientiously with regard to human safety and environmental concerns. Thus, proper characterization of water quality and quantity is an important element in managing the mine impacts on the environment and local communities.

Sources of water quality pollution differ between various ore deposit, mining and processing methods and conditions. The principles of network design are similar, but the mining extraction, processing and waste storage/disposal differ between mine types affecting the hydrologic system and water quality conditions. This chapter describes the methods for establishing monitoring water monitoring networks with respect to gold mining. In addition, an example water quality network has been developed, keeping in mind the context and processes of the Grassalco Mining Company (Grassalco) mine in the Maripaston region in Suriname.

7.2 Water Use and Pollution of Mining Activities

Mines use water to extract minerals, process ore, control dust, store ore/waste and general operation. These uses, along with alterations to the environment, have both positive and negative effects on the quantity and quality of water systems in the watershed. During operations, the hydrologic system in the catchment where a mine operates can be affected by lowering the groundwater levels through dewatering open pits and underground workings; increasing water flow in local tributaries through the discharge of pumped water or processing effluent; dewatering streams by diverting water for mineral extraction, processing and operations; lowering groundwater by pumping aquifers to support mineral extraction, processing and operations; creating ponds through developing tailing impounds; changing river flows downstream of reservoirs developed for water supply; and rerouting and obstructing streams and rivers.

Associated with metal mines, water contaminated with high concentrations of metals, sulfide minerals, low levels of pH (acid rock drainage [ARD]), processing chemicals, and suspended and dissolved solids can negatively affect groundwater and surface water quality in the catchment. Mining exposes sulfide minerals to oxygen, breaking down the minerals potentially releasing aluminum, arsenic, cadmium, cobalt, copper, iron, mercury, magnesium, nickel, lead, selenium and zinc (Environment Canada, 2001). In addition, oxidation of sulfides produces sulfuric acid and, when drained, creates ARD, which is low in pH and high in metals. For separating gold in the processing step, mercury and cyanide are commonly used. Finally, runoff water from the site can be laden with sediment affecting local waterways.

During mining, sources of pollution include open pits and underground works, waste rock dumps, processing plants, tailings dams, heap leach piles, ore stock piles, and infrastructure (haul roads, foundations, waste embankments). Effluent discharge from mining, milling or processing is discharged into surface water as well as leachate water that has trickled through solid mine waste and tailings ponds and into the groundwater may contain dissolved minerals, process chemicals, and metals (Environment Canada, 2009). Surface runoff from the mine footprint (e.g., ore and waste piles, embankments, roads) and effluent discharge may deliver elevated levels of sediment to stream networks. Hydraulic and placer mining are also sources of elevated sediment delivery to the stream network.

Following the cessation of mining activities, peak concentrations of contaminants discharged from mine sites may occur many years later. For open pit mines, delay of contaminant release arises because of groundwater and surface water filling the pit following cessations of mining, leaching metals and ARD from the oxidized minerals in the pit walls. Similarly, groundwater seeping through subsurface mining drifts leaches oxidized minerals and drains through adits (Environmental Canada, 2009). Improper management of waste material and tailing during mining can lead to widespread pollution throughout the river network for decades. For example, common practice for the lead-silver Bunker Hill Mine (in Idaho, United States) was to dispose of the tailings along the Coeur d'Alene River bank so that high-water events would carry off the material. More than 30 years after cessation of this practice, the river system still has elevated levels of cadmium, lead, manganese and zinc, prompting the river to be listed a U.S. Environmental Protection Agency Superfund Site with cleanup efforts still underway. Finally, changes to the river channel by mining activities can influence flows and reservoirs influence downstream flow regimes affecting freshwater ecosystems and the availability of water for water supply and navigation.

7.3 HIS Developments

Factors to consider when developing the monitoring network include the type of ore being extracted, method (open pit or underground workings), milling and processing method, climate, mine stage, and practices to limit use (recycling) and mitigate impacts to the environment (Fraser Institute, 2012).

7.3.1 Network Considerations

The type of network established to evaluate the impacts of mining is a project. There are multiple purposes for developing monitoring networks for mines, including, but not limited to: support design of mine site, creating environmental impact assessments, developing water management plans, monitoring site conditions to identify/mitigate pollution sources, fulfilling regulatory compliance or financial lender requirements, limiting liability and risk to false claims and enforcement violations, and improving site management. Both water quantity and quality should be monitored, with the water quality CoCs varying with the type of mining, local physiography, climate, land use and basin hydrology, as well as with regards to potentially affected ecological and socioeconomic systems.

The monitoring network should extend within and around the mine operations. In order to characterize the subsurface water entering the mine site, monitoring stations should be located upstream (surface water sources) and upgradient (groundwater sources). In some instances, waters entering a mine site may have elevated CoCs, thus the mine managers need to consider how the water is used in the operations (e.g., does it need cleaning?), as well as to document that the mine operations did not contribute water quality degradation of the inflow to the site. On-site monitoring of surface waterways and groundwater around mine workings, waste rock piles, tailings ponds and processing facilities can identify sources of CoCs and trigger measures to mitigate impacts to water sources. Surface water and groundwater at the downstream and downgradient boundaries of the property should also be monitored to determine the quality of water leaving the site. If a plume released on-site and has migrated off-site, downstream/gradient monitoring may be needed to delineate its extent and track its path. Existing monitoring network stations should be considered when selecting site locations.

Duration of the monitoring should extend from before mining begins, during development and operations, and post-reclamation to demonstrate long-term impacts associated with mining activities. Ideally, monitoring should begin at least a year prior to mine development to capture the full hydrologic cycle, but longer lead periods will capture greater hydrologic variability, thus providing better data for design and long-term management. For example, if the year preceding mine development was a wet year, then the calculations and design for the mine's water supply for processing ore may be insufficient during drier years, causing limitations in the mine operations. During the operations, the network needs to continue to be monitored, but it may need to be altered as the mining activities evolve, monitoring objectives change and data collection limits are identified. Depending on the governmental regulations, the length of time to continue monitoring following the reclamation can be a set length or criteria based. For example, for a site to be considered closed, the Idaho Department of Water Quality requires commercial and industrial sites with leaky underground storage tanks to monitor quarterly until no petroleum measurements exceed the legal criteria for a period of two years. As the effects of mining on water quality may take decades to be observed, annual sampling for decades may be required to demonstrate that no adverse impacts are arising from the mine site.

7.3.2 Sampling CoCs

As stated, the CoCs in water produced from mining include high concentrations of metals, sulfide minerals, low levels of pH (ARD) and processing chemicals, and suspended and dissolved solids can negatively affect groundwater and surface water in the catchment. Therefore, the CoCs monitored need to reflect the mine type and practices; climatic, physiographic, hydrologic and ecological conditions in the catchment; and the downstream ecosystems and human uses of water resources. In addition to guidelines presented in the previous section, sampling frequency needs to be short enough to capture mining activities. For example, if large concentrations of suspended sediment occur in stormwater runoff from a site, the sampling frequency needs to be sufficient to capture storm events. Thus, monthly sampling for suspended sediment is an insufficient frequency for sampling at this site.

Sampling fish and aquatic organisms in receiving waters downstream from mines is another method of determining a mine's impact on ecosystems (UNEP & WHO, 1996). Size, weight and metal concentration within the organism are compared between reference streams and the receiving waters to determine if chemical discharges from the mine site are affecting ecosystems. For example, in Suriname, where mercury is used by small-scale miners in processing gold, fish tissues have been analyzed for mercury and shown to have a concentration above those recommended in human health consumption guidelines in regions of small-scale gold mining (Ouboter et al., 2012). As fish is a significant food source for local communities, concentrations of mercury in fish tissue exceeding human consumption standards are a risk to local communities.

7.3.3 Supporting Infrastructure

In addition to the monitoring, other infrastructures need to be developed to support analysis and reporting. Laboratory facilities and staff are required to process water quality samples collected from the field. This includes laboratories and vehicles to transport water quality samples from the field. A data management system, as well as the hardware and software necessary for its functioning, needs to be put in place to process, store and disseminate the data water quantity and quality data. Outlining the procedures, monitoring plans and data management plans should be drafted providing methodologies, procedures, quality assurance, emergency response and staffing requirements. Finally, the monitoring network must be supported with trained staff and adequate, ongoing annual budgets. Though not as "exciting" as implementing projects, water monitoring systems are the foundation for better design, management of the project site and surrounding environment to minimize risk to both surrounding systems and the long-term sustainability of the mine site.

7.4 Maripaston Case Study

The Maripaston gold mining area (15 km southwest of Pikin Saron, Suriname) has historically been worked by small-scale mining operations. These miners use excavation and hydraulics to extract the ore from the weathered overburden. They use gravity (settling during washing) and mercury to process and concentrate gold. The mining is done in a haphazard manner with little regard to waste containment, stormwater runoff and sediment loading to streams. The activities have altered the stream channel and increased sediment, ARD and mercury loading to the stream network (see Figures 17 and 18). As would be expected, these small-scale mining operations do not have monitoring systems in place to determine the impacts to the stream network and natural ecosystems.

Grassalco has obtained the mining concession for the Maripaston area with plans to continue mining activities (Figure 19). Initial mining activities have been a reworking of the waste piles left by the small-scale miners in the northwestern quadrant of the concession. Once exploited, Grassalco will continue the operations into the hardrock below

Figure 17. Altered stream network and ARD resulting from small-scale mining activities in the Maripaston area
Photo courtesy of Carter Borden.

the small-scale miners' excavations as well as potentially mining other areas in the concession. It is understood by the author that Grassalco will use gravity to separate the gold (no mercury) and will use best management practices to control sediment and reduce runoff. In order to be in compliance with ISO 14001 standards for environmental management, Grassalco is implementing a water quality monitoring network. Using the information above, this section provides recommendations for developing a water quality and quantity monitoring network for the Maripaston project site.

7.4.1 Proposed His Network

The proposed monitoring network includes seven certain and two potential surface water monitoring sites to capture the upstream, on-site and downstream water quality conditions for evaluating impacts of current and future mining activities within the concession (Figure 19). Monitoring sites 1, 2, 4 and 9 represent upstream conditions for surface water entering the concession to provide the natural background water quality conditions. Monitoring site 3 is located downstream from current activities to determine the immediate impact to the stream network. Monitoring site 5 is along the mainstem Maripaston Creek to determine the influence of current activities downstream as well as provide an internal upstream boundary if future mining activities are extended to the eastern half of the concession. The optional site 8 captures the impacts for the boutique mining activities and provides an "upstream" boundary should mining being in the eastern half of the concession. Sites 6 and 7 represent monitoring stations that are characterizing water quality as it leaves the concession. While sites 7 and 9 may be just outside the eastern concession boundary, the accuracy of drainage network map is unclear in relation to the aerial photograph, so they have been proposed. If future mining activities where to expand into the eastern half of the property, characterizing this stream would be useful in monitoring. Note that the sites recommended in Figure 19 are the approximate locations. Site visits will be necessary for selecting the actual sampling location based on the criteria presented in Sections 3.3, 4.2 and 6.3.

As groundwater is not used in the mining process, for consumption by mine staff or by local communities, no groundwater monitoring locations have been proposed so far.

7.4.2 Constituents Of Concern

Main elements relevant for HIS design are the impacts to the downstream water quality. Of interest is the metal production, ARD and suspended sediment load to the stream network. The CoCs to collect will be baseline conditions of: temperature, conductivity, pH, DO, turbidity, metals (aluminum, arsenic, cadmium, cobalt, copper, iron, mercury, magnesium, nickel, lead, selenium and zinc)

Figure 18. Waste piles from small-scale mining activities in the Maripaston area
Photo courtesy of Carter Borden.

and suspended sediments. The preliminary sampling, along with the mineralogy of the gold deposit, will dictate the metals to sample in the future. Mercury should be sampled to demonstrate how organized mining activities, such as those conducted by Grassalco, could improve downstream water quality conditions over time.

7.4.3 Instrumentation

Discharge should be continuously measured using a pressure transducer equipped with a data logger at sites 1–7 (Table 13). These require little maintenance, are inexpensive and are easy to install. Manually read staff gauges should be installed at all sites. Monthly discharge measurements need to accompany synoptic water quality sampling in order to develop stage-discharge rating curves.

Monthly sampling is recommended for all station for the CoCs. As ARD and suspended sediment are of concern at the site, continuously monitoring pH and turbidity is recommended. Water quality sondes are recommended for stations 1, 2, 3, 5 and 6. If mining activities are to be extended in the eastern half of the concession, the instrumentation should be installed at least a year before mining development activities begin.

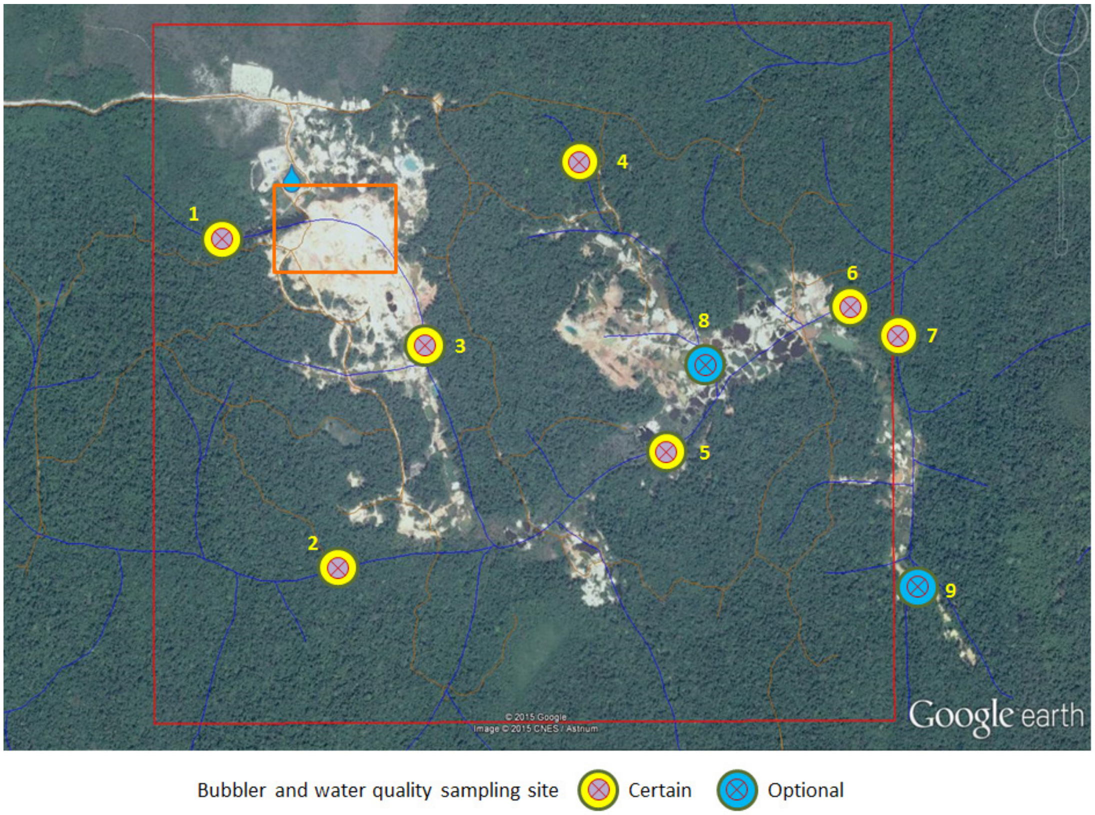

Figure 19. Proposed sampling network for Grassalco's Maripaston Mining Concession, Suriname. The red box delineates the concession boundary and the orange box denotes the active mining. Dark blue lines represent the approximate course of the drainage network with flow moving from left to right. Site locations are approximated and will be determined with a field visit and following a preliminary sampling event.

Table 13. Proposed water quality monitoring sites for Grassalco's Maripaston Mining Concession, Suriname.

SITE NUMBER	TYPE	WATER LEVEL INSTRUMENTATION*	WATER QUALITY INSTRUMENTATION
1	Certain	Pressure transducer, staff gauge, monthly measurement	Sonde, monthly grab sample
2	Certain	Pressure transducer, staff gauge, monthly measurement	Sonde, monthly grab sample
3	Certain	Pressure transducer, staff gauge, monthly measurement	Sonde, monthly grab sample
4	Certain	Pressure transducer, staff gauge, monthly measurement	Monthly grab sample
5	Certain	Pressure transducer, staff gauge, monthly measurement	Sonde, monthly grab sample
6	Certain	Pressure transducer, staff gauge, monthly measurement	Sonde, monthly grab sample
7	Certain	Staff gauge, monthly measurement	Monthly grab sample
8	Optional	Staff gauge, monthly measurement	Monthly grab sample
9	Optional	Staff gauge, monthly measurement	Monthly grab sample

7.4.4 Frequency

All sites should be synoptically monitored for discharge and water quality elements on a monthly basis. Initially, the sites may want to be visited more frequently to develop the stage-discharge rating curve and turbidity-suspended sediment rating curves. Pressure transducers and water quality sondes should be take readings every hour. If the continuous monitoring observes elevated water levels and turbidity levels during the rainy season, more synoptic sampling may be required during those periods to characterize the range of flow and sediment conditions.

7.4.5 Data Management

As the data set is small and the information is for internal monitoring and not for public consumption, storage of the data in MS Excel or MS Access database is sufficient. However, these software packages do not have quality assurance functionality, processing or standard viewing capabilities. It is recommended these capabilities be built into these platforms or a third-party software specializing in organization, storage, processing and visualization of water quantity and quality data be adopted. Once a platform has been adopted, if not already included in the monitoring plan, it is recommended that a data management plan be developed to formalize how data is processed, stored and shared and training provided to all staff handling and using the data. The data should be posted on the company's intranet for access by all relevant staff.

The availability of good quality data enables a variety of uses and ensures transparency and accountability in a variety of ways. Grassalco's environmental managers can use the data to monitor the water quality impacts of the mining activities. Therefore, reporting tools should be developed that automatically synthesizes the data into a meaningful format for quick evaluation by the managers. Such formats include maps of concentration, statistical bar charts and time graphs of CoC concentrations. Annual water quality data reports will be necessary to maintain the company's ISO 14001 certification. Externally, the data can be reported over the web and annual report. By reporting the water quality results, Grassalco demonstrates to local communities, current and future investors, government agencies, interested stakeholders and the general public that they are concerned with environmental stewardship as well as the health and well-being of local communities.

7.5 Conclusions

Establishing an HIS network to monitor water quantity and quality provides the basis for characterizing the watersheds as well as the impacts of development such as mining on the project site and surrounding environment. The data can be used for regulatory compliance, limiting risk, infrastructure design, obtaining ISO 14001 certification, assessing impacts to downstream aquatic ecosystems and determining the efficiency of mining processes. Furthermore, the data can be used to determine if mining activities are affecting water and food security for local communities.

Effective HIS monitoring and reporting provide transparent and useful data and information for monitoring the physical state of watersheds, as well as the impact of mining systems on water resources. This detailed assessment can provide short- and long-term information relevant to understanding water security and WEF security in the context of mining.

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