Chapter 7

Selecting monitoring equipment

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7.1 INTRODUCTION

Integrated Urban Water Management should be based on true, measured data, with assessed uncertainties (as discussed in Chapter 6). Monitoring equipment, specially designed for the measurement of certain parameter(s), is used to obtain such data. A number of monitoring devices are available on the market and the task of optimal design and equipment selection is therefore not easy. Selection of monitoring equipment is typically made subsequent to the establishment of the goals and objectives of the monitoring programme (Chapter 3). The selected equipment has to not only fit the purpose, but the available budget, desired precision and accuracy and appropriate scale (e.g. a turbidity sensor used in a drinking water reservoir will need to be optimized to a different scale than, say, one used at the inlet of a wastewater treatment plant). It also has to cope with spatial variability of measured variable (Chapter 5), to work within on-site environment conditions, to work continuously between inspection and maintenance periods and to be able to be readily (and reliably) calibrated under field conditions. Relevant government laws and contract agreements should also be checked for possible selection constraints. Contract agreements for the purchase of measuring devices often dictate required measurement systems. These constraints may be in terms of accuracy, specific comparison of devices and procedures.

In order to assist the reader in the difficult job of selecting monitoring equipment, according to the principles given in the previous chapters, some basic guidance regarding sensors are given. Important sensor characteristics are listed, and the criteria used for the choice of monitoring equipment explained, considering the need to integrate different components of the urban water cycle.

7.2 DEFINITION OF TERMS AND HISTORICAL OVERVIEW

Monitoring can be defined as regular sampling and analysis of air, water, soil, wildlife, and other factors, to determine, for example, the concentration of contaminants and to track system behaviour and its response to management. Sampling is done using *monitoring equipment* devices (typically electrical) used for measurement of various parameters (after NDWR, 2000).

The primary role of the monitoring equipment is to convert some measured non-electrical quantity, such as water level, into an electrical quantity that can be stored and processed. This conversion is done within the element called a *transducer*, a device that converts one type of energy into another, or responds to a physical parameter (Labor Law Talk, 2005) for the purpose of measurement of a physical quantity or for information transfer (ANST, 2000).

Since the 1970s, the term *sensor* has been used widely instead of transducer. The sensor is a device that detects or senses a signal or physical condition. Most sensors are electrical or electronic, although other types exist. The sensors can either directly indicate the values (e.g. a mercury thermometer or electrical meter) or are paired with an indicator (perhaps indirectly through an analogue to digital converter, a computer and a display) so that the value sensed becomes readable.

In general, a history of the sensor development can be divided into two parts: one prior to the semiconductor era and the period where semiconductors have been used in order to improve the sensitivity, reduce the size and integrate the sensing and indicator functions. According to the level of integration, the sensor development can be grouped into four generations (Stankovic, 1997):

(1) Raw sensors (resistive sensors, inductive displacement sensor, etc.)
(2) Sensors with built in amplification and temperature stabilization, with analogue output
(3) Modern hybrid sensors with analogue and/or digital output, and the possibility to perform some data analysis (the direction of the data is still only from the sensor to the instrument)
(4) The latest generation of sensors with built-in two-way communication capability and additional instrumentation. The sensor itself knows its calibration data, transfer function, and so on, and is not just used to communicate between different sensors and the user, but to perform the more complex data analysis. The use of such a general purpose instrument permits easy expansion of the measuring chain.

Still used in many situations, typical monitoring equipment of older generation consists of the following components (Bertrand-Krajewski et al., 2000):

- Sensors, with or without an internal amplification,
- Amplifier with a conditioner that will amplify and normalize a week signal from the sensor and also filter out the unwanted signals or average the measured signal,
- Transmitter that will output standard current or voltage signal proportional to the measured quantity,
- Display, with or without local registration unit, and
- Power supply (battery, solar panel, or mains connection).

A block diagram of the older instrument is shown on the left of the Figure 7.1. The basic characteristic of such a system is its passive role in monitoring: it can only collect and send data without any possibility to interact with environment. The more modern digital instruments (Figure 7.1, right) discussed in Section 7.3 below offer greater possibilities.

7.3 MODERN MONITORING EQUIPMENT

In the modern digital instruments (Figure 7.1, right), the microprocessor controls all functions of the instrument and since the sensor itself has the microprocessor too,

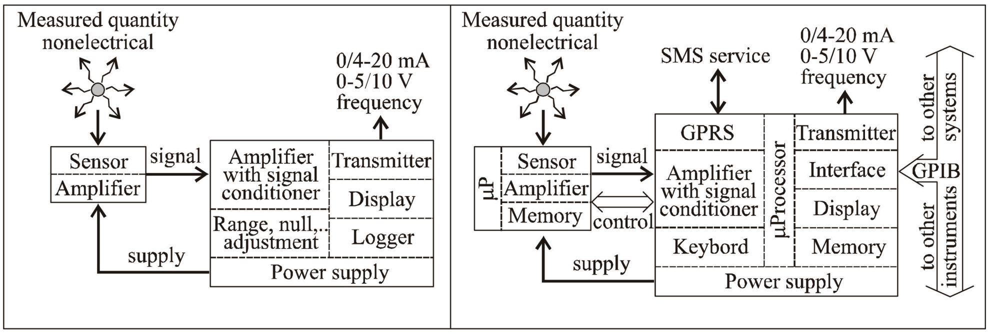

Figure 7.1 Diagramatic representation of monitoring equipment: old analogue instrumentation (left) versus new digital systems (right)

it can exchange the data and change the working parameters as needed. The data preprocessing can be done, and the instrument can communicate with the hierarchically dominant system, either by wire, fibre optics, or wirelessly. Such measuring systems are usually called *intelligent systems*, since they can *react and adapt to the measured variable*, in order to maintain the highest specified operating parameters. If turbidity of water is measured, for example, the operating range of a transparency sensor can be altered automatically if the concentration of suspended solids in water changes significantly, thus maintaining the maximum accuracy throughout the whole measured data.

Multi-parameter sensors are the state of the art in sensor development: the same sensor can now simultaneously measure more then one quantity, saving space and significantly reducing cost. For example, there are new sensor chips only 25 mm square with the capacity to measure temperature and five water quality parameters on their surface: free chlorine, monochloramine or dissolved oxygen (configurable), pH, redox and conductivity. The chip is manufactured on a ceramic substrate; it has no membranes, buffer solutions or glass bulbs, so a robust monitoring station can be constructed. When linked with a tiny low-power computing platform and wireless communication with aggressive power saving algorithms, a number of such stations will form a low-cost wireless sensor network for monitoring water supply and sewer systems (WSSS) (Stoianov et al., 2004). New developments in this field are happening all the time, and the reader is advised to seek out local guidance from both providers and users of such equipment.

7.3.1 Sensor characteristics important for equipment selection

In urban water related projects a number of different quantities are used. Those quantities that user can continuously monitor could be grouped as follows:

- Physical properties of water (temperature, density, viscosity, etc.),
- Quantities that describe current state of flow (level, pressure, velocity, etc.),
- Chemical parameters of water (pH, suspended solids, organic load, inorganic load, nitrates, nitrites, toxic substances, etc.),
- Biological content of water (total coliform bacteria, etc.),
- Climate (rainfall, air humidity, air temperature, solar radiation, etc.).

Apart from the listed quantities, data on a number of geometric quantities are also needed, such as the diameter or shape of a pipe, as mentioned in Chapter 4. Acquisition, accuracy assessment and handling of the geometric quantities, although being of equal importance, are not covered by this chapter.

For each measuring quantity, the user can find a whole range of sensors on the market, based on different working principles. Even sensors with the same working principle, if equipped with more or less sophisticated instrumentation, will produce varying results. A number of good textbooks (e.g. Stankovic, 1997; Miller, 1983; Boros, 1985) and internet sites are available describing in detail individual sensor operation, range of usage, and the availability of sensors for measuring certain quantity (Muste, 2003). Those texts are oriented mostly towards either a certain group of users or types of measurements (laboratory measurement, sediment measurement, measurement in sewer systems). To avoid repetition of those details, we list here only basic characteristics common to all types of sensors and vital for good selection of equipment:

Accuracy/uncertainty and repeatability of the sensor: These are the two most important parameters (see details in Chapter 6). Basic accuracy is closely linked with the sensor's principle of operation while accompanying instrumentation can slightly improve or impair the operation (there are some examples where the manufacturer deliberately compromises accuracy in order to lower the market price). Repeatability is even more important than the accuracy: if the sensor is not accurate, it can be recalibrated, but only in the range of its repeatability.

Accuracy and repeatability of the whole measuring system: This is rarely assessed by the user, although the overall accuracy of the system is always lower then the accuracy of the sensor itself. The sensor has to be matched to field measuring conditions. For example, the ultrasound-based water-level measurement is widely used and is highly accurate, but only for clear and still water surfaces, without floating foam and debris, as commonly occurs in 'real' water systems. Similarly, the theoretically high accuracy of the ultrasound transit-time method of flow measurement in closed pipes will be largely reduced if the water is not homogeneous. Through final data validation (explained in Chapter 8) measures of the overall accuracy should be determined, and this uncertainty used in the reporting of any final output (Chapter 6).

Stability: Defined as constancy of repeated measurements, particularly over time, and under changing conditions, stability has two components: (a) long-term stability under constant working conditions, defined as a drift of the output signal per month or year, and (b) thermal stability, defined as a change of the output signal for a rapid temperature change of working environment. Thermal stability is important if the monitoring station must operate throughout the calendar year, especially in harsh conditions where variations in temperature can be up to 100°C. Specification of permitted time-drift and temperature-drift should be made when selecting sensors, based on allowable uncertainties specified in the objectives.

Resolution: Resolution refers to the capability of the measuring equipment to distinguish between small differences in an input signal (measured quantity). For analogue equipment, the resolution is theoretically infinite and is therefore practically equal to the noise level. Digital equipment is by its nature limited by its resolution. Contemporary digital equipment has minimized this problem using high-resolution converters (more than 16 bit) and auto-ranging options (automatic gain-adjustment). It is important to match the resolution of the sensor with all other components of the entire monitoring system (e.g. data logger, communication lines) to avoid degradation of the measured data.

Linearity: Some sensors are by their nature non-linear (for example, the rate of light absorption is nonlinear to the concentration of suspended solids). If the principle has good repeatability, the microprocessor can be used to linearize the output. But even being linearized, the non-linear system will not have constant relative error along the measuring range; the highest error will be in the range of maximum sensitivity.

Measuring range (or dynamic range): This is the range of change in a sensed quantity that can be measured with specified accuracy. For most sensors this range is 1:10, although a few can have a range of 1:100. The producers often specify an extended measuring range, where equipment can be used but with lower accuracy. For some sensors, exceeding the measuring range will cause permanent damage to the instrument (for example, differential pressure sensors are sensitive to overload, since the diaphragm can be damaged).

Dynamic response (slew rate, response time): This is a measure of how fast the sensor reacts to a sudden change of an input quantity. In general, three situations are possible:

(1) The input variable can have rapid changes in value, but the user is not interested in these, and the monitoring system need only record mean, averaged values. An example of such a case is measurement of daily pressure variations in pressurized pipes, where only mean values are needed and not peaks caused by transients. Filtration of the rapid transients can be done mechanically (using special housing constructions), electronically or combined.
(2) The user wants to measure rapid changes. Response time of the equipment is fundamental and it has to be matched with expected rate of changes in input variable. In some situations, using inverse Fourier transformations or convolutions in time domain, the frequency response of the equipment can be linearized. However, the user has to be aware of the large volumes of data generated by such equipment.
(3) The third situation is a mixture of two: when the user wants to measure mean values during certain periods (when river level is slowly changing, for example) and switch to fast response when certain conditions are fulfilled (e.g. as the flood wave is approaching). In the latest generation of monitoring equipment, the user can interact with control software to change the instrument's behaviour in different situations, and the monitoring stations themselves can communicate with others to exchange current data and information on their operating status (arrays of sensors).

7.3.2 Criteria for the selection of monitoring equipment

Selecting the proper measurement device for a particular site or situation is not an easy task. A good knowledge of physical, chemical and biological processes at a measurement site is needed, as well as knowledge of different sensor's techniques applicable to those processes. Technical parameters are not the only criteria that should be considered. Other factors (ecological, financial, institutional, etc.) will often impose constraints that will limit the list of the possible monitoring equipment.

Throughout Chapters 3 to 5, the objectives and applications of the monitoring, the selection of variables, and consideration the temporal and spatial variability, were discussed. Bearing in mind the need to integrate the measurements in urban water systems in a way that different users can share the data, a checklist of items that a user should consider when selecting the appropriate monitoring equipment is given below. The list should be seen as a guide only (not compulsory instruction), and the user is also advised to consult other local sources and guidelines (e.g. USBR, 2001). The relative importance of each item in this list depends ultimately on project objectives.

Users of data: Identify and consider the needs of both current and potential users. Some possible uses of data include: (i) real time control (RTC), where online data are important. and users will not bother with data storage and post-processing; (ii) numerical simulation models, where a vast amount of short-term and long-term historical data are needed and the exact conditions of the system state are important; (iii) legal requirements for trade metrology, mostly regulated by government with the equipment regularly checked for accuracy specification; (iv) storage of historical data, performed by national or state institutions, for some (identified or unidentified) future need; and (v) system control and system management, the most demanding use, as data users need online data similar to short-term, mid-term and long-term historical data and also data mining and data extraction techniques.

Continuous monitoring versus ad hoc measurements for different purposes: Ad-hoc measurements could be a viable alternative since they are much cheaper and can cover a wider spectrum of measuring techniques, but with much more human involvement (and usually with bigger problems of sampling representativeness). A special kind of ad hoc measurements are diagnostic measurements, when higher accuracy equipment is used in order to quantify the values of certain parameters. Examples include the measurements of pump characteristics, natural frequencies for some construction, and the roughness factors for pipes.

Measuring accuracy: The user has to decide what is the required accuracy of measured data (based on the objectives and allowable uncertainty), and calculate how this will influence the whole project. Specification of the allowable uncertainty (and thus allowable inaccuracy) becomes a critical specification for monitoring equipment. As a rule of the thumb, the accuracy of equipment used should be at least three times better then the required. Typically, however, the price of monitoring equipment will be approximately exponentially related to its accuracy.

Possibilities to calibrate and recalibrate the equipment: To maintain rated accuracy, each piece of the measuring equipment has to be calibrated prior to its installation, and then periodically recalibrated (as suggested by the manufacturer). Also, the user has to verify the instrument after it has been installed at a measuring site (although the accuracy of available methods for such verification is generally lower). Ease of calibration, and the methods for verification of the equipment, should be key considerations in equipment selection. Modern measuring equipment should follow '**g**ood **l**aboratory **p**ractice' (GLP) standards (AGIT, 2003) and allow storage of the calibration results in the internal memory, forming a database where long-term behaviour of the equipment can be checked. If this is not the case, the user will need to keep a database of calibration results, in order to understand this behaviour.

Ability to check the whole monitoring station: Whenever possible, perform tests of the equipment by inputting a known volume or quantity of the measured variable. For example, in flow measuring devices in small sewers, one can drain the whole tank of known volume into the upstream manhole. Through later data analysis, volume added to the base flow can be deduced, providing an effective check of the equipment.

However, do not forget to note the event in the database as a test event, so that the results do not become mixed with the data from the true rainfall event.

Available resources: The following resources should be considered: (i) finances; (ii) time, since in most situations measurements are to be conducted at very short notice (maximum flow during floods, for example); (iii) available space for sensors and monitoring stations, especially for water quality measurements where a number of parameters are needed (the reason manufacturers have developed multi-parameter sensors); (iv) The level of education and skill of staff to operate the equipment; (v) power supply (battery, solar charger or regular mains supply) and the implications of this for service and reliability; and (vi) communication possibilities (telephone lines, GPRS signals, optical cable) and their implications for service and data downloading.

Available techniques for measurement: During the process of equipment selection, all available techniques should be considered. The most accurate technique is not always the most suitable; issues of robustness and system compatibility may be paramount. Monitoring equipment selection charts (Figure 7.2) are commonly available for most monitoring variables (USBR, 2001).

Sizing (working range): Monitoring systems should work within its optimal range of values of measured quantity. Choosing a device that can handle larger than necessary input values could result in elimination of measurement capability at lower (or higher) values, and vice versa. For practical reasons, it may be reasonable to establish different accuracy requirements for high and low values of measured quantity. To assess needed measuring range, it is convenient to use hydraulic modelling software (e.g. HEC-RAS (USACE, 2005), EPANET for water supply systems), or other models, (depending on the variables to be monitored) to predict likely ranges of behaviour. In the simulated environment, the number of needed measuring points and ranges for each sensor can be optimized using different criteria (Kapelan, 2002). Besides a static working range, the dynamic response of the equipment has to match expected variations of the input signal to avoid aliasing (deterioration of the signal due to insufficient sampling frequency).

Conditions at the measuring site: The selected device should not alter site hydraulic conditions so as to interfere with normal operation and maintenance. Also, the basic accuracy of the selected device should not deteriorate as a result of hydraulic conditions or the measuring site selected. Figure 7.3 provides an example of flow measurement where the flow conditions changed from rapid (supercritical) to tranquil (subcritical) and

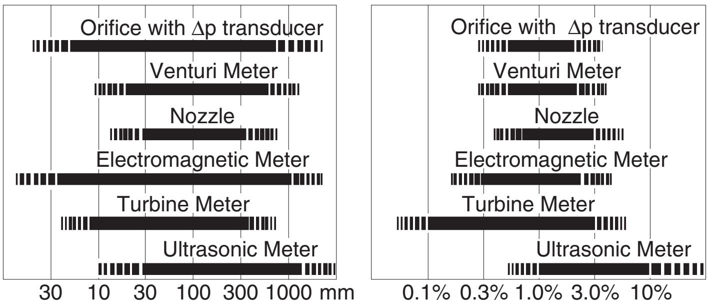

Figure 7.2 Suitability of pipe flow measurement devices as a function of diameter (left) and accuracy (right)

Source: Adapted from Radojkovic et al., 1989.

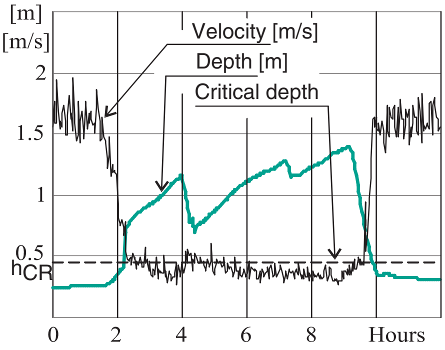

Figure 7.3 Change of flow regime due to varying downstream conditions

Source: SI, 2004.

then back to rapid, due to gate operation downstream (SI, 2004). A stream hydraulics simulation model such as widely-available HEC-RAS (USACE, 2005) software can help the user to simulate and determine optimal position for flumes, weirs, or other controls.

Sensors with local storage: The current trend in production of new equipment is the addition of local storage capacity of each sensor. This will lower the risk of data loss: if supervisory equipment is out-of-order, the sensor will still work and collect the data; upon the re-establishment of communication, the sensor will report the locally stored data. However, the monitoring equipment now has to cope with possible ambiguity: as measured data are stored in the sensor and in the main database, data mismatch can occur. Appropriate data validation procedures should be implemented to address such possibilities (see Chapter 8).

Sensors with inbuilt communication capabilities: Nowadays sensors are often equipped with local wireless communication capabilities. In most cases this is not the primary method of sensor communication with other sensors in supervisory system (usually there is a centralized telemetry controller), but this allows the user to occasionally check the sensors' functionality and to obtain current readings through simple inquiry. Of course, data security then becomes an issue that has to be addressed, since the sensor readings are potentially can be intercepted (for example, using a mobile telephone).

Sensors with built in intelligence: In addition to local storage and communications capability, many sensors are able to: (a) analyse gathered data (e.g. find extreme values, statistical values, slope of data, etc.); (b) change their own function according to some programmed logic (e.g. when slope of input data is higher than a certain threshold value, the sampling rate should be increased; if this is happening too often, the threshold value should be changed and reported to the user); (c) apply the results of recent calibration that are stored in each sensor (which allows online change of the sensors, e.g. if pH sensor is replaced, the instrument will detect this and read the new calibration parameters and apply them to the measurements, writing this event into the log-file); and (d) report to the user if measurements are suspicious (through an SMS or other telemetry service). A number of sensors can thus be organized into several distributed monitoring stations, each communicating with each other. For example, if the automatic sampler has to take samples of clean water just before a cloud of suspended solids approaches the station, the upstream sensors will announce the coming event and the monitoring station can calculate the exact time when the first sample has to be taken. Based on previously measured concentration of solids, the sampler can be operated in a programmed regime.

Time synchronization: IUWM will require that measurements from a diverse range of monitoring equipment are integrated, to allow analysis of interactions to be undertaken. To allow easy data integration, it is necessary to have synchronized measurements with local time accurate to within one-third of the shortest measuring time increment, Δt. Nowadays, with the proliferation of the global satellite positioning system (GPS), an accurate synchronized clock signal should be used.

Robustness and sustainability of equipment: Monitoring equipment in general is expensive. The user has to consider the ability to use the same equipment at several locations, with different sampling criteria and working parameters. Highly dedicated, closed systems are better for permanent monitoring stations, but if equipment is to be shared among several users, it is better to have an open, user programmable system.

Coherency of all elements within monitoring system: All elements within the monitoring system (Figure 7.1) should match with their parameters: accuracy, resolution, and dynamic response. As a rule of the thumb, the sensor and conversion principles are the most critical parts of the chain, and so rest of the equipment should have better parameters. A common mistake is to use the analogue 4 mA to 20 mA output (mostly with 1% accuracy) to transmit the measured signal to the main computer and then convert it into the digital form with a 0.01% accuracy converter.

Environmental limitations: Not all environments are sensor friendly and not all measuring techniques are environmentally friendly (e.g. some tracer techniques). The user has to analyse potential mutual impacts and to design protective measures. For example, the most expensive water quality probe will be useless if a floating plastic bag wraps around it, or if an aggressive water environment melts the cast aluminium housing. The measuring method can also influence the environment. For example, installing a weir or flume constricts the channel, slows upstream flow, and accelerates flow within the structure. These changes in the flow conditions can alter local channel erosion, local flooding, public safety, local aquatic habitat, and fish movement up and down the channel. For stream systems with high sediment loads, placement of a properly sized Parshall flume or low-head, sharp-crested or drop-box weir can help ensure that sediment flows through the flow control.

Operating conditions at measuring site: Conditions critical for proper operation and longevity of devices include suitability of power supply (stable source of supply), presence of vibrations (in vicinity of pumps, for example), direct sunlight (the temperature in a closed cabinet under direct sunlight can go up to 60°C or 70°C), high humidity (up to 100%), corrosive and aggressive environment (even in some clean water reservoirs), extremely low temperatures (most batteries will deplete in such conditions and in freezing water devices with moving parts in contact with water will stop functioning), and the concentration of debris (e.g. in rivers, especially during flood events). The potential for vandalism, especially in open field sites, has to be considered and proper housing selected.

Field/construction works: Installation will often be a limiting factor. For example, the flow in a sewer system can be easily and accurately measured using a critical depth flume. But the construction of such flume in an old, continuously operating sewer trunk is almost impossible (or, at least, not economically feasible).

Training of users and after sale service: The general trend in development of the measuring equipment is to hide its complexity from the user with 'intelligent' processors that will optimize the sensor operation according to local conditions. To keep the overall accuracy within the equipment's specified limits, however, it is essential to train the user for correct instruments usage (for example, the meaning of different parameters within the instrument, and the explanation of error messages, etc.). After-sale service and support is important: it may be better in some situations to select lower quality equipment with good, experienced local support, than to purchase the latest technology product that nobody in the surrounding area is capable of servicing or supporting.

7.4 SPECIFIC CONSIDERATIONS FOR DATA INTEGRATION WITHIN IUWM

What specific criteria for measuring equipment might apply to deliver a better integrated monitoring system across all components of the water cycle? Firstly, the underlying considerations discussed in the previous sections of this chapter remain important, and cannot be ignored. However, for data to be efficiently shared between different users, working across different water cycle components, the most important task is to *keep the data and monitoring system well documented*. This applies not only to the name and serial number of the sensors used sensors, but also to descriptions of the measuring site including sketches and/or photographs, hydraulic and environmental conditions, equipment conditions, battery voltage and internal temperature. Importantly, the results of accuracy assessment for the sensors and for the whole system, history of sensor calibration, explanation of data storage format used, should all be rigorously documented. All such 'added' data that accompany the primary measured data are called *metadata*, and more details regarding the collection, storage and utilization of metadata are provided in Chapters 9 and 10.

During the design phase of the monitoring site, it is essential to handle the metadata with the same attention as the primary measured data. One part of the metadata will be created by the monitoring equipment itself. Contemporary measuring equipment in most cases will follow the GLP standard, and will store data about working conditions and calibration results. Another part of the metadata will be created during data validation phase (Chapter 8), while some of metadata has to be added manually, such as descriptions of site, observations and exceptions, and timing of additional tests. *The monitoring programme must define metadata that is compulsory, considering all possible future users of the data, across all potentially relevant water cycle components*.

7.5 SPECIFIC CONSIDERATIONS FOR DEVELOPING COUNTRIES

When selecting the monitoring equipment, the overall development of the region has to be considered too. Modern equipment means higher initial costs and the need for educated users to establish the network and to conduct regular inspections, recalibration and maintenance. The problem is emphasized if the measuring equipment is part of a development assistance programme: in most situations, the donated equipment will be of the latest generation, where the initial high cost is covered by donor programme, but later operating and maintenance costs need to be covered by local users. The benefits from such programmes would be much greater if the equipment installed is manufactured by local companies and part of available resources are spent on the education of both local manufacturers and local users.

During the process of monitoring station optimization, the price/performance ratio should be thoroughly considered. In general, the ratio is not the same for countries with high standards where working labour is very expensive and for developing countries where 'human-powered' monitoring may be relatively less expensive. When new monitoring equipment has to be installed in developing regions, it is advisable to introduce the technology step by step: firstly the systems of older generation (which will often be relatively less expensive and usually robust), to allow the users to accept the technology, to develop skills and learn the basics. Over time (and depending on the need) new, more expensive smart systems can be installed. It is critical, however, that the selection of monitoring equipment matches local needs and context. Spending large amounts of money on unnecessarily complex and sophisticated equipment, without a clear need to do so, is likely to result in redundant and unused equipment, thus wasting already limited resources.

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