Chapter 15

# Water supply

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## 15.1 INTRODUCTION

From the very beginnings of urbanization, the water supply system (WSS) performed a central role. The ancient Egyptians, Greeks and Romans constructed systems to capture, store and distribute water using the same basic approach as is used today: capture, lifting, storage, treatment and distribution to consumers. Valves and pumps are used to manage the distribution, while storage reservoirs are used to balance temporal differences in supply and demand.

In the earliest WSSs, the only information collected was whether adequate water availability existed. Over time, monitoring levels increased, partly as water supply has gone from an entirely public-good function to a commonly commercial operation, where profit optimization drives the need for data (Obradovic, 1999). In such an environment, real information about captured and delivered water, as well as accurate data regarding water quality issues enables both system-control and evaluation of economic viability.

In most cases measurements in contemporary WSSs are integrated within existing informatics support systems (Maksimović and Prodanović, 1995) (e.g. Figure 15.1). While these systems offer great capability, they require ongoing maintenance and upgrading, and their original design, if not carefully thought out, will limit performance.

Water supply systems are just one component of the complex urban water system, and the interactions between components are critical (see for example Chapters 1 and 13). Accordingly, the WSS needs to be able to exchange data with other external systems (see for example Chapters 9 and 10). The data exchange can be either continuous online as data are acquired (for example, the WSS can send to local authorities or can publish directly on the internet the content of chloride and turbidity of water for selected sites within the water distribution network) or off-line, as exchange of historical data, at specified (systematic or ad-hoc) times. Regardless of the online or off-line data exchange, it is important to follow the recommendations given in Part I of this book: the measuring site and equipment have to match the monitored variable requirements, the uncertainty has to be assessed, measured data validated and metadata used to store the sensor position, measuring conditions, calibration curves and validation results.

The water supply system is a complex system with a number of separate but connected components: water intake (withdrawal), conveyance of untreated water, water treatment, conveyance of clean water, water quality conditioning, reservoirs (storage), distribution network, and finally, the consumers (or water customers). Each subsystem has its

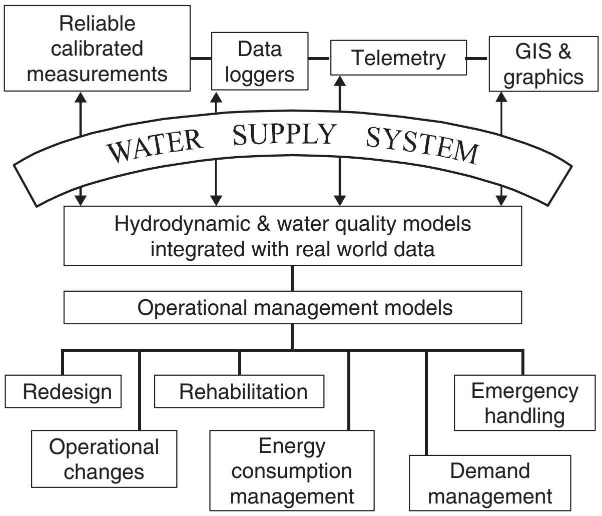


*Figure 15.1* Components of an integrated informatics support system to water supply systems (WSS)

*Source*: Maksimović and Prodanović, 1995.

own required variables for status evaluation, control and optimal operation. In the next subsections a short description of the monitoring requirement for each of these components will be given.

Within water supply systems, water is often a 'product', and thus legally regulated metrology has to be used to quantify its movement and consumption. There are also other important roles of measurement in WSS, namely, *for process control, water balance check, modelling purposes* and for *diagnosis of system details*.

## 15.2 INTERACTION WITH OTHER URBAN WATER SYSTEM COMPONENTS

The water supply system makes up just one component within the complex urban water environment. It is closely coupled with other urban water systems (Table 15.1). The WSS monitoring programme must therefore take into account those interactions and acquire enough data to evaluate them. Collected data should be shared between systems and merged within one common database (Chapter 9). Storage of metadata (e.g. place and conditions of measurement, sensor type and manufacturer, calibration data, real time and date of measurement) is essential for effective use and sharing of such data.

## 15.3 SPECIFIC REQUIREMENTS WITHIN WATER SUPPLY SUBSYSTEMS

Each subsystem (intake, storage, treatment, etc) within the WSS has to be monitored and managed in order to optimize its performance. Data requirements for each subsystem are provided in the following sections. Of critical importance to all components is

*Table 15.1* Potential interaction between water supply systems and other urban water system components

| *System component* | *Potential interactions with water supply system* |
|---|---|
| Urban climate | Precipitation, temperature and evapotranspiration will influence demand, particularly for outdoor uses.<br>Evapotranspiration will affect losses from water supply stores.<br>Temperature will influence chemical treatment and water quality in water stores and supply networks.<br>Extreme events such as severe freezing, or floods, may result in damage to urban water supply infrastructure. |
| Wastewater and combined sewer systems | Improper wastewater disposal may pollute drinking water supplies, resulting in reduced water availability and/or increased treatment cost.<br>Increased consumption of drinking water means larger flow rates in the wastewater system, whilst a reduction in drinking water consumption will reduce dilution and affect treatment processes.<br>In leaking water supply systems, wastewater can be sucked into the pipe and mixed with clean water if pressures fall below zero.<br>Clean water from leaking water supply networks can infiltrate the wastewater system, changing the quantity and quality of wastewater and affecting the operation of treatment facility. |
| Stormwater | Stormwater may impact drinking water quality, especially in mixed land-use catchments.<br>Stormwater may provide an alternative water supply, for potable or non-potable purposes (e.g. rainwater tanks, large-scale stormwater harvesting).<br>Potential interaction of stormwater and water supply networks, where leakages in water supply pipes exists. |
| Groundwater | Leakage from the water supply network will increase the groundwater recharge and potentially increase the groundwater table.<br>Urban or suburban groundwater is the main source of clean water for many systems, so monitoring and protection of groundwater is vital. |
| Aquatic ecosystems and urban streams | The discharge of polluted and cold water from mains or reservoirs can degrade aquatic ecosystems.<br>If urban streams are in direct or indirect connection with clean water withdrawal, the quantity and quality parameters of streams will affect water supply system.<br>Extraction of water from waterways will affect the flow regime. |
| Human health | Operation of the water supply system will determine the level of risk to human health (from toxic substances, or from bacteria and/or viruses).<br>Cross-connections or leaks into the water supply distribution network could result in contamination, causing human disease or long-term health effects. |
| Society and institutions | Community preferences and attitudes will determine the required (a) security of supply and (b) water quality. For example, community attitudes will determine whether use of recycled water is acceptable, and will affect water conservation during times of drought.<br>The roles and responsibilities of institutions will affect how water is supplied. For example, a government agency with responsibility for water, wastewater and waterway management may have a different approach than a private company with responsibility only for supply of drinking water. |

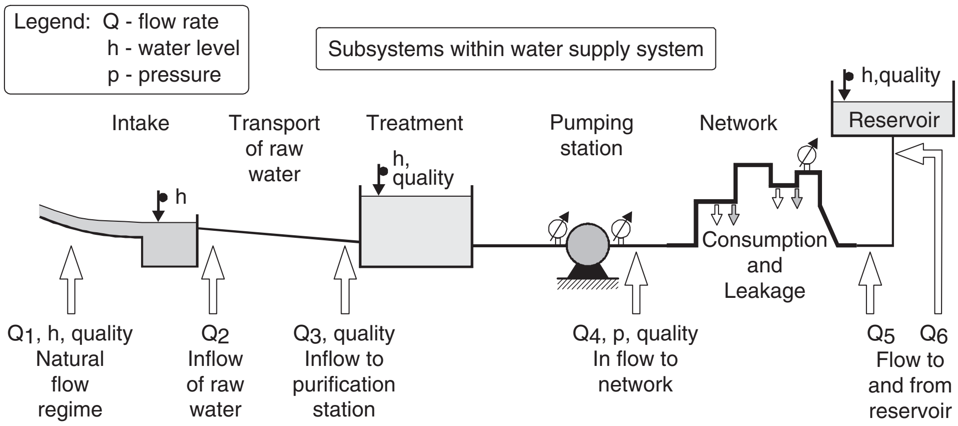


*Figure 15.2* Diagram of subsystems within a water supply system and required measurements for water balance calculations

*Source*: Maksimović, 1994.

the necessity to have a mass balance. This means that the flow rate, pressure or level, and important quality parameters of input and output must be continuously measured (Figure 15.2) and recorded, to allow instantaneous and integrated values to be obtained.

### 15.3.1 Water intake

The water intake (withdrawal) is the input point to the WSS, and can be either from natural streams (as shown in Figure 15.2), from groundwater or from other connected WSSs (i.e. as part of a regional system). The intake is usually considered as a 'point of exchange', since the WSS typically has to pay for taken water from the point of withdrawal.

The measurements at the intake should cover all important processes, including potential disturbances on water flow and quality in the system from which water is being extracted. Depending on the type of intake point, the following monitoring should be undertaken:

- *Natural water streams*: continuous measurement of upstream and downstream water levels, flow rates (if possible with direct measurement, otherwise calculated using rating curves) and upstream quality parameters (including point-source pollutant sources). Periodic measurements of bed profile near intake structure, to identify any siltation or erosion processes.
- *Lakes or dams*: continuous measurement of inflow and water level, as well as downstream flow rate (particularly if downstream environmental flows are stipulated). Influences on the groundwater table (see also Chapter 19) have to be monitored using boreholes and piezometric wells. If siltation of the lake is important, the bed profile has to be regularly checked. The changes in water quality parameters in

lake occurs with seasonal variations and are depth dependent, so it is important to continuously measure at least the temperature, turbidity and dissolved oxygen at several water depths.

- *Groundwater*: continuous measurement of level and flow rate in each well and quality parameters for the whole wellhead. Monitoring of the groundwater table using boreholes and piezometric wells, near the wellhead and in the wider area subject to extraction.
- *Water intake from another (larger, regional) WSS*: water level in reservoir, quality parameters and extracted flow rate. Usually, two flow meters are used: one owned by the owner of the regional WSS and the other one by the WSS that takes the water.

The water intake subsystem is closely linked with the other water components. The availability of water depends in most cases on rainfall (and evaporation), surface water inflow or recharge of groundwater from other systems. Monitoring of those resources is mostly carried out within other systems and organizations, so efficient data sharing take place. To minimize the effect of water pollution on WSS operation, a set of proactive measures are needed (catchment protection, back-up sources, etc.), which can be assisted by efficient collection, processing and exchange of monitored upstream water quality data.

Some common problems associated with the measurements of water intakes are:

- In most cases, measuring positions are far from urban areas, so vandalism, lightning damage, availability of electricity and data communication reliability all present challenges.
- The raw, captured water can contain dissolved gases (even explosive) which can be aggressive to certain type of sensors, can be corrosive, or sometimes can result in deposition. The selection of measuring sensors has to take into account the nature of the raw water, and the frequency of sensor recalibration will need to be increased.
- The exchange of data between different water related systems means that each system has an important role to play. Commonly, the water supply utility will be primarily interested in only current data for its own part of the water system. However, this precludes understanding of potential impacts on the water intake quality and quantity by other parts of the water cycle. In other words, this approach is often shown to be short-sighted.

### 15.3.2 Conveyance of untreated and clean water

The water transport system can be either for raw water (from the water intake to treatment plant) or for clean water (between the source of clean water and distribution network). Associated pumping stations are also considered as a part of transport subsystem.

Assuming that there is no consumption along the distribution line, water losses can be simply calculated by measuring inflow and outflow of the transport subsystem (Figure 15.3, Alegre et al., 2000). Even in more complex pipe systems, with several

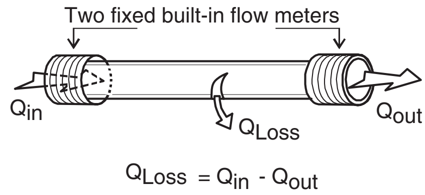


*Figure 15.3* Locating flow meters to monitor water loss in water transport pipes

*Source*: Maksimović and Prodanović, 1995.

main pipes, it is advisable to have a pair of flow meters for each pipe section. With such an arrangement, it is easy to monitor the pipe performance and its leakage rate. If a sudden pipe burst occurs (during earthquakes, for example, or during excavation works) it will be detected and shutting down the service valves thus prevents excess leakage (Gotoh *et al.*, 1993).

The quantities to be continuously monitored in the water transport system are:

- *Flow rates*: apart from the instantaneous flow rate, the cumulative volume of passed water has to be recorded. Small and cheap sensors can also be used for direct monitoring of leaks (Halsey et al., 1999).
- *Pressure at selected points*: where the number of sensors and their positions mostly depend on the type of the flow regulation. Using pressure and flow data, a pipe's hydraulic conductivity deterioration can be assessed.
- *True position of regulating valves*: regardless of control type (manual or automatic).
- *Pump operation parameters*: pressure, upstream and downstream of the pump, voltage, current and the cumulative working period; especially, in systems with variable frequency control, the operating frequency must also be monitored.
- *Water quality*: the selection of water quality parameters to be monitored depends on, among other factors, the transport water. In general, the quality of water deteriorates in long and large transport pipes with small velocities. New developments in micro-sensor design for water quality monitoring (Stuetz, 2001) will reduce the cost of such equipment and will allow more widespread application in pipe networks.

Some important general considerations to be borne in mind for monitoring water transport systems are:

- Flow measuring device should be capable of measuring bidirectional flow, since that can occur in some systems.
- Flow meter calibration, critical in transport systems, can be a challenge, since in most cases the diameters of pipes are large.
- When selecting the number of measuring positions and types of sensors, it is good to have redundant measurements using different sensor typed for quality control and to assess the overall measurement accuracy.

- Long and large pipes are prone to water hammer and oscillation (often induced by inadequate functioning of control elements). In such systems it is wise to have a transient pressure monitoring device (Prodanović *et al.*, 2004). Standard pressure loggers are not suitable, however, due to long sampling intervals.

### 15.3.3 Water treatment and water quality conditioning

Treatment is required in practically all water supply systems. As the availability of clean water is decreasing and the demand by customers for high quality water is increasing, the need and the complexity of treatment plants is also increasing.

Water treatment plants are complex units with (in most cases) automatically controlled processes. A number of quantities are continuously measured and the operation of a treatment plant depends on the accuracy and availability of that data. The overall efficiency of a treatment plant is controlled at its outlet, where at least two separate monitoring systems are used: one continuous system based on built-in sensors, and the other one through regular sampling of water and manual (laboratory) water testing. Through regular data comparisons, the possibilities for errors in treatment plant operation are reduced and water quality is maintained within specified limits.

In spite of having a number of sensors, Supervision, Control, Data Acquisition and Data Analysis (SCADA) systems and manual tests of water in laboratory conditions, sharing of resulting data with other water cycle managers is often difficult, particularly because SCADA systems are often closed and the data are often regarded as 'commercial-in-confidence'.

Apart from water treatment plants, in large WSSs *water quality conditioning units* are also often used. They are situated along the clean water network and their role is to maintain the water quality, in most cases by controlling the amount of residual treatment, such as chlorine.

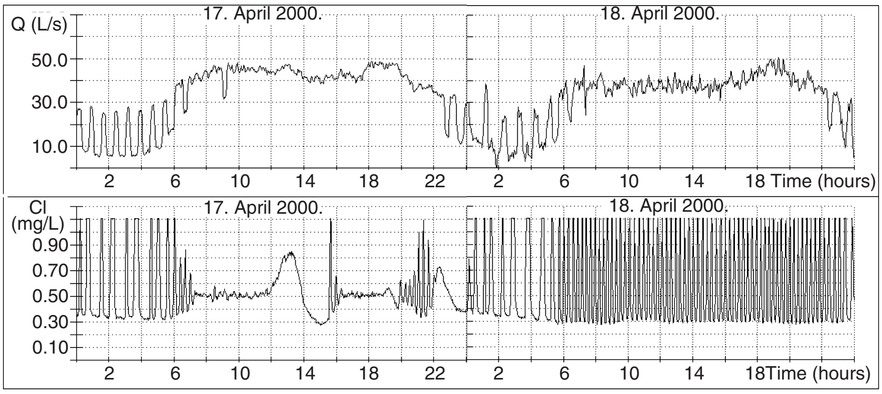


*Figure 15.4* An example of dynamic mismatch between pipe flow and automatic chlorine dosing station. The sudden changes of flow (Q) through pipe (upper diagram) due to nearby pump causes the oscillation of automatic chlorine dosing system (measured residual chlorine Cl on lower diagram)

*Source*: Prodanović et al., 2001a.

Issues related to the monitoring of water treatment plants and water quality conditioning units include:

- Measurements within treatment plants are used for real-time control and most systems are not designed to store historical data.
- Measurements are vital for real time control. For example, inaccurate flow measurements (or an incorrectly positioned turbidity meter) could result in overdosing of chemicals.
- The dynamic response of the water treatment system to sudden changes of input parameters and dynamic response of measuring equipment should be matched. Fast reacting ('nervous') dosing controllers are dangerous (see Figure 15.4, where an automatic chlorine dosing station failed to keep the residual chlorine level at a constant 0.5 mg/L, due to sudden changes in flow rate – upper diagram, and starts to oscillate, raising the average residual chlorine much above the limited value – lower right diagram) (Prodanović et al., 2001a).
- There are commonly a number of chemical parameters measured off-line within laboratories. It is possible to establish the correlation among those parameters and parameters that are continuously monitored online, so that online monitoring can be used as a surrogate measure. The format of output data should include the metadata, to allow easy exchange with other data users.

### 15.3.4 Reservoirs

Reservoirs are used for temporary storage of water, allowing the operation of the water treatment plant to be independent of current water consumption, and balancing temporal variations in supply and demand. The storage volume of the reservoir and its position within the network is typically the subject of a detailed study using network simulation models. Different layouts are possible (DOH, 2006) and the optimal solution based on given criteria should be found (Kapelan *et al.*, 2005).

For monitoring reservoir behaviour, the necessary parameters include inflow, outflow and water level. Depending on the type of reservoir, inflow and outflow pipes are either separated (two flow meters are needed) or the same pipe is used. A bidirectional flow meter is needed, with separated counters for direction toward the reservoir and direction from the reservoir to the network. Adding the continuous water level measurement, a redundant system is created, where accuracy checks of measured quantities can be performed.

In some WSSs the residual chlorine is checked within reservoirs and is increased, if needed. This is especially important within reservoirs where water may remain for days without recirculation, as is the case with large reservoirs constructed for potential future water needs, or during the low water consumption season, within systems with large seasonal variations.

### 15.3.5 Distribution networks

From the main transport pipe, water is distributed to the customers through the distribution network. The distribution network can be divided into several levels: primary (the largest pipes that are connected to the main transport pipe, with connections of important and large customers and mostly without house connections), secondary (with less important connections, fire connections) and tertiary (small diameters with hose connections or network within large houses). In order to limit the maximal pressure, the distribution network is always divided into pressure zones, where the number of zones depends on topography.

The orthodox approach to the distribution network is to design it with redundant connections (looped system) and not to monitor its behaviour. Repairs and maintenance will then often be based on customer complaints or observed leaks. However, if the network is to be operated in an optimal way, with the minimal number of bursts, reduced leakage and maximized output performance (increased reliability of clean water delivery to the customer), a proactive approach must be used.

The proactive approach means that the distribution network has to be continuously monitored. Measured quantities (pressure, flow, turbidity, residual chlorine, valve status) from numerous positions should be a part of complex online telemetry system. A sampling interval of 10 minutes to 15 minutes should be used in smaller systems, or even shorter for larger pipes. SCADA systems can be used to automatically check the water balance at each time step. If a mismatch occurs, the alarm signal should be sent to the field crew. To reduce the number of false alarms due to communication problems, sensor malfunctioning or other reasons, the system should be equipped with some kind of self-learning mechanism, such as neural networks or expert systems (Kohonen, 2001).

The prerequisite for a good distribution network monitoring programme is its division into smaller parts, with known input(s), output(s) and with flow meters installed (Figure 15.5). Such areas, commonly known as **d**istrict **m**etering **a**reas (DMA) (Thornton, 2002), and they should cover about 150 to 200 house connections, although this number may considerably vary from one WSS to another. Within each DMA the input flow (and output, if any) is continuously monitored and the difference between night (low flow) and day (high flow) readings are analysed on a daily basis.

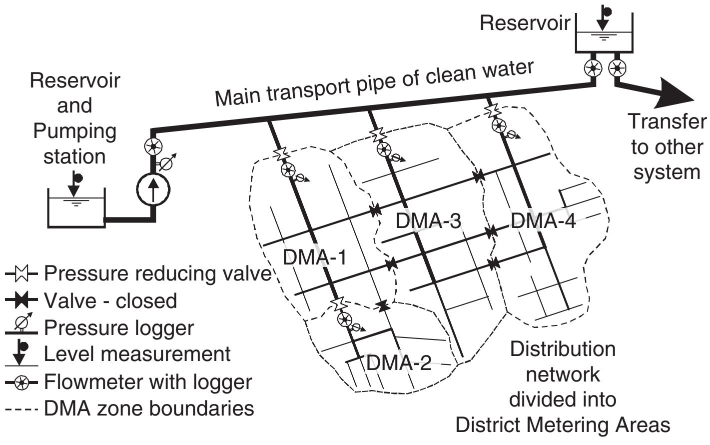


*Figure 15.5* Water balance must lie measured and calculated within manageable units of the distribution system (e.g. District Metering Areas, DMAs)

*Source*: Obradović, 1999

Connecting the databases of house water meter readings and continuous measurement of inflow (and outflow) will enable evaluation of the water balance for each DMA. To reduce network leakage, the DMA can be also equipped with pressure regulating valves (PRV) which will maintain the pressure at the minimal acceptable value (Figure 15.5).

There are two possible approaches to network management after the introduction of DMAs. The first one is to keep each DMA separated from the rest of the system, and continuously monitor its parameters. This situation is presented in Figure 15.5, with black valves in closed status. Another possibility is to prepare the network for the DMA, equip the necessary pipes with flow and pressure meters, but allow certain redundancy by opening some interconnection valves. This will increase the reliability of network and make the detection of sudden bursts more difficult. In such an approach, the field crew should continuously test all DMAs by separating one at a time from the network for at least 24 hours and afterwards checking the water balance.

Figure 15.6 presents some possible outcomes of DMA monitoring. The left-hand graph is the result of continuous measurement of flow within one DMA (Obradović, 1999), where it is noticeable that a pipe burst during December (and was repaired the next year). The right-hand graph presents one 24-hour test of a DMA where measured flow was almost constant, without any night flow reduction (estimated water loss up to 90%)(Prodanović et al., 2001b).

Recommendations regarding measurements and data analysis on the distribution network include:

- Calibration of flow measurement sensors is difficult within the water distribution network, due to irregular flow conditions. Other techniques (such as the velocity method or volume method) will be needed to calibrate flow sensors, in order to compute water balance within required accuracy.
- To optimize the value of data collected by the WSS, a 'data management plan' should be prepared at the commencement of monitoring (Babovic et al., 2002).

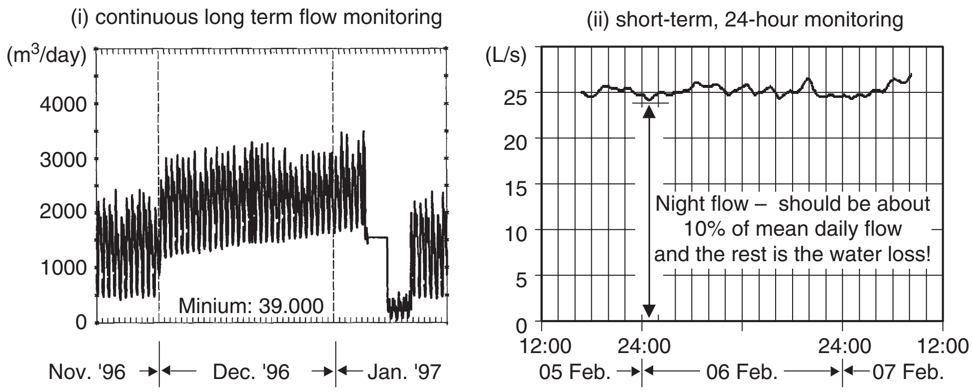


*Figure 15.6* The results of monitoring two district metering areas: (i) continuous monitoring can reveal the development of a crack in a pipe (Obradović, 1999) and (ii) short-term (24-hour) diagnostic monitoring of system with high water losses (Prodanović et al., 2001b)

- Water balance computation has to be undertaken within each DMA, several DMAs, as well as an entire pressure zone. When doing water balance calculations, it is helpful to keep track of flow meters with lower accuracy, and to use redundant measurements to correct the overall result.
- Advanced data-mining techniques (Chapter 10) are needed to manage the large quantity of measured data. Using redundant measurements, the number of false alarms can be reduced, by pattern detection methods.
- Apart from the monitored hydraulic and quality data, geometric data about pipes (i.e. position, diameter, material, roughness, etc.) and other objects within the network (i.e. valves, pumps, etc.) should be as accurate as possible. Any changes in the network should be updated within databases and simulation models.

### 15.3.6 Consumers

Monitoring customer consumption is possibly the most important requirement of the water supply system. Using mechanical, mostly turbine water meters, the total volume of water is measured, often by manual meter reading. The interval between readings depends on the significance of the customer and varies between once per month and once per year. In such systems the rate of successful meter readings can be below 60% to 70%, due to a large number of blocked or damaged meters, or even meters with unknown location. Knowing that the average age of installed water meters is usually well above the regular service period (five years in most countries), it is reasonable to be suspicious regarding any water balance calculations that are derived from aggregation of customer meter readings.

The most common errors in customer readings are either propeller blockage or a reduction in the propeller rotation speed reduction, both resulting in reduced reading and large negative errors in the measured volumes. Another problem with water meters is low sensitivity to small consumption (for example, continuous pipe leakage will not be measured). There are several solutions to this problem, such as using smaller water meters that are more sensitive to low flow, or using combined flow meters (one for small flows, and one for larger flows).

Most WSSs have some kind of database which maintains the water meter readings. The input of data is variously manual, semiautomatic (from handheld data input devices) or automatic (using remote meter reading systems). Apart from the production of invoices for water consumed, the data provides an opportunity for analysing system operation and performance. Different socio-economic information is easily extractable from this type of data. Extraction of demand patterns in large WSSs will be facilitated by use of the data-mining techniques.

Integration of the water meter readings database with the other information systems within the WSS is a difficult task, and is therefore rarely undertaken. For example, the time steps for water meter reading are variable (making matching to other data more difficult), as is the accuracy (diminishing with meter age). Matching the individual meter readings to simulation models of the entire network can also be difficult.

## 15.4 THE ROLE OF MEASUREMENT

Measurements play a very important role in the operation of water supply systems. Measurements may have a simple objective, such as pressure measurement to test a pump's normal operation, or can be used for several tasks (the same pressure measurement at the pump's outlet can be used to evaluate its performance, to monitor the status of downstream reservoir, to monitor the overall consumption, and be logged for later use as calibration data for a numerical simulation model).

In general, measurements in WSSs can be classified as:

- measurements for the purpose of charging for the water,
- measurements for continuous checking of water balance and calculation of water losses,
- measurements for process control and diagnostic purposes.

To achieve better data integration, it is important to identify all possible data users and their needs for additional metadata before a monitoring system is established.

### 15.4.1 Measurement for selling water

The WSS is usually the only component of a complex urban water system where water is regarded as a product. It is extracted from nature as a material, and the WSS adds new value to it through its treatment (quality improvement), pumping (raising its energy), storage and delivery directly to the customer.

In order to sell the product, it has to be legally measured, so legal metrology has to be applied at the customer's connection. In most countries water meters must comply with certain standards and regulations. For example, in Europe, in 2004 the EU Parliament adopted the Measuring Instruments Directive (MID) 2004/22/EC for different meter types, where general conditions for their application, installation, accuracy, calibration and ranges are given. The OIML (*Organisation Internationale de Métrologie Légale*) and all EU countries must follow the MID.

Legal metrology must also be applied in water withdrawal, since the WSS typically has to pay for water extraction. Depending on local policy, the price of taken water will consist of the maximal flow rate, the volume of water taken per period, the potential energy of water and the quality of water. In certain countries, the local authority can introduce an additional charge as a function of WSS leakage factor, to encourage the water supplier to reduce leakage and preserve the water resources.

### 15.4.2 Calculating the water balance

Measurements of input and output from the system, as needed for billing purposes, may produce only a total water balance of the whole system. The difference between input and output, as total water loss, cannot be allocated to any specific WSS subsystem without additional measurements within those subsystems. Figure 15.2 gives the minimum requirements for flow and level measurements so that the water balance can be calculated. There are also guides (e.g. Alegre et al., 2000) on how to assess the water balance and how to express it using performance indicators.

Since the data from different subsystems are used for water balance calculation, it is important to have enough metadata, mainly regarding the type of meter, its diameter, measuring range and typical accuracy within the range, low-flow threshold, calibration results and position within the network. The flow measurement accuracy on large pipes has to be better than 1% (typically 0.5%), level measurement accuracy better then 0.5% (typically 0.2%) and pressure 1% (if it will be used for pipe condition, the monitoring the accuracy has to be better than 0.2%, it must have atmospheric pressure correction, and its height must be known with an error of less then 0.05 m). For smaller pipes, the flow measuring accuracy can be in the range of 1% to 2%.

The period for data acquisition (or sampling rate) depends on the rate of flow and pressure changes at the measuring position. If the sampling rate is low (e.g. 5 minutes to 15 minutes) the error in flow integration will rise during periods of rapid changes in flow rate. A typical flow log is presented in Figure 15.7 (left), sampled with short time steps (continuous line, sampling every second) and with more infrequent, every 100 seconds (diamond dots). The difference is not so obvious, but if volume of water is calculated (Figure 15.7, right) then significant differences will appear during periods of rapid flow rate change. However, very high sampling resolution will increase requirements on data storage (see also Chapter 5 for temporal scale considerations). The solution for this problem is to acquire two types of data from each flow measuring device: one is the continuous flow rate that can be used for monitoring and control purposes, and the other is the total volume passed through the meter and internally integrated, to be for use for water balance calculations.

Understanding (and subsequently managing) water balance is the critical requirement in a WSS, since it determines how efficiently the clean water, a scarce resource, is used. A number of organizations are working hard on the education of water companies and local authorities (WHO, 2001), creation of 'best management practice' for water conservation (Water Forum, 2006) or definition of water audit methodology and water loss control (AWWA, 2006; UKWI, 1994). Tables 15.2 and 15.3 outline the water balance scheme and definition of water balance components as defined by IWA/AWWA. Redundant data will help in the calculation of water balance, and pressure measurements, while not directly used in calculating the water balance, can help

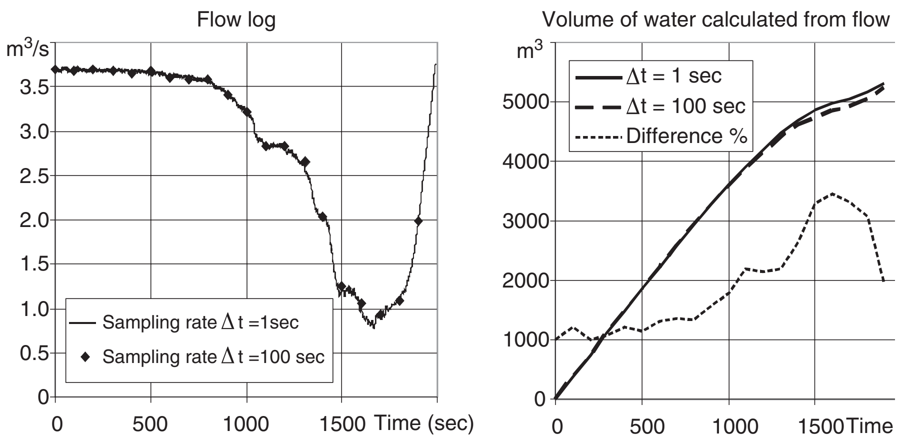


*Figure 15.7* Illustration of the impact of the choice of sampling rate on the recorded flow and calculated water volume

*Table 15.2* Tracking water use for calculation of a water balance[1]

| | | | | |
|---|---|---|---|---|
| System input volume[2] (corrected for known errors) | Authorized consumption[3] | Billed authorized consumption | Billed metered consumption (including water exported)<br>Billed unmetered consumption | Revenue water[7] |
| | | Unbilled authorized consumption | Unbilled metered consumption<br>Unbilled unmetered consumption | Non-revenue water[8] (NRW) |
| | Water losses[4] | Apparent losses[5] | Unauthorized consumption<br>Customer metering inaccuracies<br>Data handling errors | |
| | | Real losses[6] | Leakage from transmission lines and distribution mains<br>Leakage and overflows at utility's storage tanks<br>Leakage at service connections up to point of customer metering | |

Notes:
1 All data in volume for the period of reference, typically one year.
2 Annual input volume to the water supply system.
3 Annual volume of metered and/or unmetered water taken by registered customers, the water supplier and others who are authorized to do so.
4 Difference between system input volume and authorized consumption (apparent losses plus real losses).
5 Unauthorized consumption, all types of metering inaccuracies and data handling errors.
6 Annual volumes lost through all types of leaks, breaks and overflows on mains, service reservoirs and service connections, up to the point of customer metering.
7 Components of the system input volume which are billed and produce revenue.
8 Difference between the system input volume and billed authorized consumption.
*Source*: Farley and Trow, 2003.

to understand water balance results, since water losses are a function of pressure (Tabesh et al., 2005).

### 15.4.3 Process and water quality control

Each automatic control system is based on some kind of measurements. It may be as simple as control of inflow into a reservoir where level indicators (discontinuous level measurement) are used to close and open the input valve, or as complex as a chemical dosing system within water treatment plants. The general problem with such measurements is that data are usually not accessible by other users (the system is closed to increase its reliability).

Therefore, during the design stage of the automatic control system, it is important to decide what quantities are potentially needed by other users, as well as their required time scale and format. A secure system can then be constructed to transfer these data to other users, without impacting on security of the primary system.

### 15.4.4 Diagnostic measurements

Continuous measurements used for WSS management and water balance calculations are usually inadequate for analysis of the system details or system operation in irregular conditions. Additional measurements, targeted to the given problem, are commonly

*Table 15.3*

FPO

referred as *diagnostic measurements*. Such measurements, when combined with the existing monitoring system, will provide valuable additional data about the behaviour of individual system elements, and help in solving the given problem (water hammer when the pump is switched off, for example). The measures can also provide the additional data needed for calibration and verification of numerical simulation models.

Diagnosis of problems within the WSS must comply with precisely defined requirements and planned objectives which are to be achieved (Prodanović and Pavlović, 2003). Depending on the final objective, a suitable selection of measuring methods and equipment can be undertaken, as well as selection of data processing tools. Diagnostic measurements consist of several steps:

- *Measurement*: the choice of measurement equipment mostly depends on the problem to be addressed. In general, more accurate equipment is needed than the equipment typically used for continuous measurement. Logistical challenges (such as changes to normal operating procedures) will often make diagnostic measurements more difficult.
- *Analysis*: data preprocessing, validation and advance analysis of system behaviour in both static and dynamic conditions. The analysis gives information for a proposed solution.
- *Accuracy assessment*: each measured variable has a certain error. Using accuracy assessment, the overall error in the final result can be computed. To reduce the total error, the measured data has to be as accurate as possible, but also some redundant data is needed.
- *Cost–benefit analysis*: presents an important part of the diagnostic measurement. The water authority needs to know a technical solution to the given problem, as well as the costs and benefits of a proposed solution.

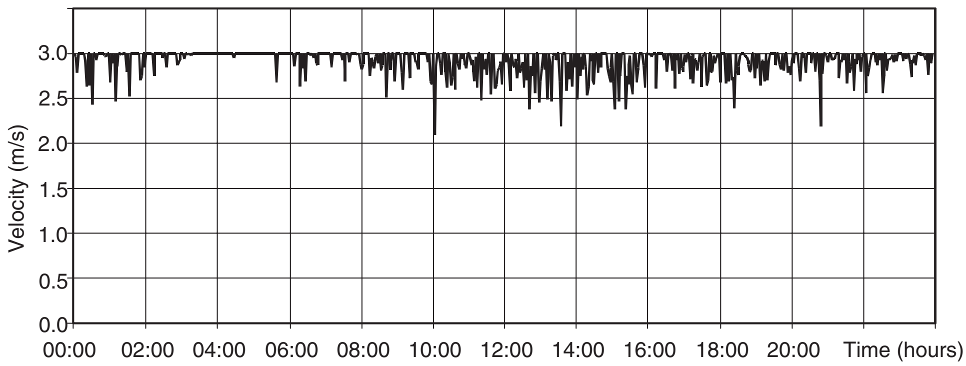


*Figure 15.8* Example of velocity measurement on previously unmonitored system (with incorrectly–selected instrument range, limited to 3 m/s). The example shows that for systems where there is no prior-knowledge, two measurement campaigns will be needed with the first providing the information to refine the second

*Source*: Prodanović and Pavlović, 2003.

Diagnostic measurements cover a wide field of applications. In general, several types of diagnosis can be identified:

*Standard flow and pressure measurement on distribution network*, for calibration of numerical simulation model or for network performance assessment. This is the most common type of measurement. The number of flow and pressure loggers depends on the available resources. If there is no previous knowledge about the network or the expected measured range and flow direction are unknown, at least two series of continuous measurements should be conducted. The first one will give general information about the system. Rough calibration of the numerical model should be performed based on that information. Using the model and a site visit, the possible critical parts of the WSS are detected. In the second series of measurements, some new measurement locations should be selected, focusing on the observed problems. Figure 15.8 presents an example of flow (velocity) measurement, in a case where there was no previous information about the system. Velocities were measured with an electromagnetic probe, which is generally able to measure velocities up to 10 m/s, but during the signal conditioning procedure they were limited to 3 m/s. Since obtained velocities were much above 3 m/s, some checks were done on mathematical model. It turned out that two level zones were directly connected through that pipe and water was flowing from high pressure zone to low pressure zone, producing velocities significantly beyond those which were expected.

*System details diagnosis*, such as flow measurement in large pipes for recalibration of flow meters that are working in non-standard conditions. For example, Figure 15.9 shows a plot of true, or measured, pump stage-discharge characteristics, compared to the standard curve as from the pump's specification. Diagnosis may also

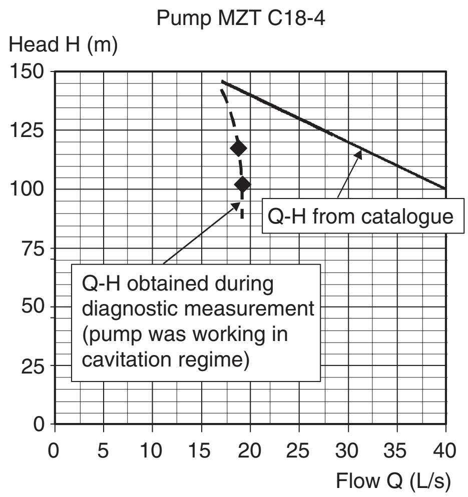


*Figure 15.9* Diagnostic measurements could reveal the true pump specification. Diagram shows the result of measurements on the pump that works in cavitation regime, thus having the Flow-Head (Q-H) curve much different then expected (H = height, Q = discharge)

(*Source*: Prodanović and Pavlović, 2003).

be used for flow in irregular conditions, water hammer analysis, water mass oscillations in long pipes, filter performance in regular and overload conditions, or searches for partly closed valves within system or connections. Such measurements must be undertaken with more accurate equipment than would be used for standard operational monitoring.

*Leakage loss diagnosis*. Continuous monitoring provides the best approach for this purpose, with change detection algorithms used to detect the occurrence of leaks. For small leaks, monitoring systems capable of accurately measuring low flows will be required.

*Diagnostic measurements during abnormal circumstances*, such as pipe breaks, bursts, water hammer, and other events. To be most useful in this context, monitoring of the pre-incident network state is required (so that changes can be detected).

## REFERENCES

Alegre, H., Hirner, W., Baptista, J. and Parena, R. 2000. *Performance Indicators for Water Supply Services: Manual of Best Practice*. London, International Water Association.

AWWA (American Water Works Association). 2006. *Water Loss Control, Conservation by Water Suppliers*. Available at: http://www.awwa.org/WaterWiser/waterloss/index.cfm (Accessed 02 July 2007.)

Babovic, V., Drecourt, J.P., Keijzer, M. and Hansen, P.F. 2002. A data mining approach to modelling of water supply assets. *Urban Water,* Vol. 4, No. 4, pp. 401–14.

DOH (Division of Environmental Health, Office of Drinking Water). 2006. *Water System Design Manual*. Available at: http://www.doh.wa.gov/ehp/dw/publications/design.htm (Accessed 02 July 2007.)

Farley, M. and Trow, S. 2003. *Losses in Water Distribution Networks – A Practitioner's Guide to Assessment, Monitoring and Control*. Cornwall, UK, IWA Publishing.

Gotoh, K., Jacobs, J.K., Hosoda, S. and Gerstberg, R.L. 1993. *Instrumentation and Computer Integration of Water Utility Operations*. Denver/Tokyo, American Water Works Association Research Foundation/Japan Water Works Association.

Halsey, G., Lewin, P.L., Chana, G. and White, P.R. 1999. Intelligent sensor for water leak detection and location. Paper present at Sensor and Transducer Conference, 17–18 February 1999, Birmingham, UK.

Kapelan, Z., Savic, D. and Walter, G.A. 2005. Multiobjective design of water distribution systems under uncertainty. *Water Resources Research*, Vol. 41, pp. W11407.

Kohonen, T. 2001. *Self-Organizing Maps*, 3rd edn, Vol. 30. Berlin, Springer.

Maksimović,. Č 1994. Measurements for diagnostics and rehabilitation of water supply systems. *ASI: New Technologies for Large Water Supply Projects*. Varna, Bulgaria.

Maksimović, Č. and Prodanović, D. 1995. Hydroinformatic support to poorly documented leaking water supply systems – an integrated approach. Paper presented at International Conference on Advanced Technologies for Saving Water, 6–7 February 1995, Athens, Greece.

Obradović, D. 1999. *Contemporary Water Works. Informatics and Operational Management*. Belgrade, Serbia,Yugoslav Association for Water Technology and Sanitation (in Serbian).

Prodanović, D. and Pavlović, D. 2003. The role of diagnostic measurements in poorly maintained and documented water supply systems. *Proceedings of XXX IAHR Congress, 24–29 August 2003*. Thessaloniki, Greece, Aristotle University of Thessaloniki and International Association of Hydraulic Research,.

Prodanović, D., Pavlović, D. and Ognjanović, M. 2001a. Automatic control within waterworks – two examples. Paper presented at Twenty-first National Congress of Waterworks and Sanitation. 17–19 October 2001, Novi Sad, Serbia (in Serbian).

Prodanović, D., Ljubisavljević, D., Pavlović, D. and Babić, B. 2001b. *Diagnostic Measurements on Herceg Novi WSS for Numerical Simulation Model Calibration. Field Study*. Faculty of Civil Engineering, University of Belgrade, Serbia (in Serbian).

Prodanović D., Ivetić, M. and Savić, D. 2004. Dynamic monitoring and leakage detection by induced transients. *Proceedings of 6th International Conference on Hydroinformatics, 21–24 June 2004,* Singapore, Hydroinformatics Society of Singapore.

Stuetz, R. 2001. Using Sensor Arrays for online monitoring of water and wastewater quality. *American Laboratory Journal*, Vol. 33, No. 2, pp. 10–14.

Tabesh, M., Asadiani Yekta, A.H. and Burrows, R. 2005. Evaluation of unaccounted for water and real losses in water distribution networks by hydraulic analysis of the system considering pressure dependency of leakage. Paper presented at Conference Computing and Control in the Water Industry (CCWI) – Water Management for the Twenty-first Century, 5–7 September 2005, University of Exeter, UK.

Thornton, J. 2002. *Water Loss Control Manual*. McGraw-Hill.

UKWI (UK Water Industry). 1994. *Managing Leakage Reports*. Swindon, UK, WRc plc/Water Service Association/Water Companies Association.

Water Forum. 2006. *Water Conservation Annual Report*. Available at: www.waterforum.org/WaterConservAnnualReport.pdf (Accessed 02 July 2007.)

WHO (World Health Organization). 2001. *Leakage Management and Control: A Best Practice Training Manual*. Available at: http://www.who.int\docstore\water_sanitation_health\leakage (Accessed 02 July 2007.)