Urban water supply automation – today and tomorrow

Gustaf Olsson

ABSTRACT

Automation is a collection of a whole set of theories and methods to make a system work automatically as intended, in our case the urban water supply system. A critical feature of automation is the feedback principle: a sensor is measuring a certain variable, e.g. a concentration; a computer tests that the measurement is valid; a computer algorithm calculates and decides what should be corrected; a pump or valve or some other device transforms the decision to action. All of this is untouched by human hand. The 'intention', or the goal, must be provided to the controller. The key component of automation is the system that can represent any component or process in the water supply system and even the complete system. Automation technology always must be combined with a true understanding of people at all levels. Otherwise, there is a high risk for misunderstandings and failures. Three categories of problems are highlighted, where automation can contribute: uncertainty, feedback, and complexity. A key challenge is the handling of disturbances. Integrated management of the whole urban water cycle will be required in future urban areas to acquire sustainable operations. Automation is a crucial condition to make integration possible in complex systems.

Key words | complexity, control, disturbances, feedback, integration, uncertainty

Gustaf Olsson
Industrial Automation,
IEA, LTH, Box 118,
Lund University,
SE-22100 Lund, Sweden
E-mail: *gustafolsson3@gmail.com*

HIGHLIGHTS

- Dealing with uncertainties by online monitoring.
- Using feedback at all levels to correct deviations from 'normal' operation.
- Handling disturbances, particularly in time scales too fast or too slow for human interaction.
- Operating complex highly interactive systems as well as small-scale decentralized systems.
- Operation of the integrated urban water supply system.

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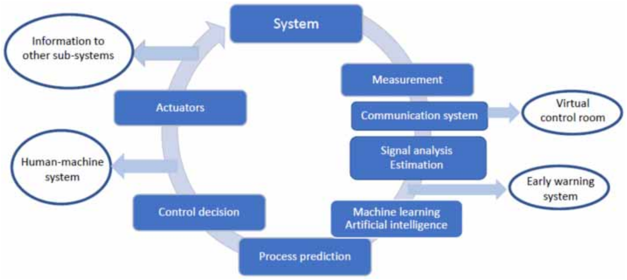
GRAPHICAL ABSTRACT



THE URBAN WATER CHALLENGES

Urban water supply and treatment is a matter of life and death. In our urbanized lives, we easily forget our connection to, and dependence on, nature. With increasing population and urbanization, higher demand from industries and food production, intensified by climate change and more erratic precipitation patterns, the balance between human water use and nature is threatened. This has a profound impact not only on water supply and treatment, but also on the demand on more efficient use of water at home, in industries and in agriculture. The close coupling between water and energy has an impact on both water and energy structures.

Automation technology should play a significant role in future urban water systems. However, we emphasize that it is only part of the answer. If technology is not combined with a true understanding of people – within the water utilities and among users and customers – then it will be exceedingly difficult to reach the sustainability development goals. Technology and automation systems are simply enablers of organizations, people, and business decisions.

The awareness that water is fundamental to life should have a sincere impact on how we extract, treat, use, and return water to nature. If water is in abundance, we seldom pay attention to any imbalances in nature. As expressed by Ingildsen & Olsson (2016): 'There needs to be some kind of water stewardship that ensures that the urban and the natural water cycles work together seamlessly and without destroying values in either place'. We need to acquire a better understanding of the relationship between urban water systems and the surrounding nature, not only in general or in global terms but also in each specific location. So, the water sector needs to prepare for all the collateral effects of climate change, where water is a primary indicator. To put it into the words of the British TV presenter and naturalist Sir David Attenborough: '… above all it will require a change in perspective. A change from viewing nature as something that's optional or 'nice to have' to the single greatest ally we have in restoring balance to our world'.

Some of the challenges facing any urban water system, where automation should have a role, include:

- *Integration*: There are considerable risks associated with outdated silos thinking, where no one sees the whole picture, no one is responsible, where it is impossible to pool budgets and decision-making is too fragmented. We need to consider our whole water system including the use of water for other purposes, not only agriculture and industry but also the ecological quality of freshwater systems and oceans. Automation not only demonstrates the need for integration but also makes integration possible.
- *Asset management*: Many water systems have been in place for 50–100 years already. Automatic monitoring of assets is a cost-effective way to continue their service and renew them in a sustainable way.
- *Reducing energy consumption*: By applying monitoring and control. It also opens the management and use of decentralized plants, using renewable energy sources, and considering economic and social issues.

- *Source water*: water quality protection is a prime challenge for any water supply. Automation should play an increasing role in ensuring safe water using real-time quality supervision and control.

The technology push

Instrumentation, control, and automation (ICA) attracted the attention of the water and wastewater industry in the early 1970s (Olsson *et al.* 1973; Olsson 2012) and is currently widespread in all kinds of water operations. To date, the primary function of ICA has been to keep treatment systems running efficiently, achieving the desired performance at affordable cost, in the presence of large fluctuations in loads, while at the same time abiding with environmental standards. In recent years, there has been a greater emphasis on the use of ICA to improve the capacity of existing systems and make them better able to cope with external disturbances or internal malfunctions. In this context, the individual plant is no longer regarded as a stand-alone unit, but a node in a net-centric architecture in which its operation is harmonized with that of all the other units.

The technology development today should have a profound impact on the operation of water supply systems. Low-cost sensors and low-cost and yet powerful microchips will have a tremendous impact on promising measurements. Internet of Things (IoT) together with large data storage capacity will make huge amounts of data available. Collecting and utilizing large amounts of data have never been greater in urban water systems (Eggimann *et al.* 2017). This, in turn, requires fast computing, for example iCloud computing, necessary to handle big data. Furthermore, advanced analytical data handling is developing via machine learning and artificial intelligence (AI).

THE HEART AND SOUL OF AUTOMATION

The word automation is related to the Greek word *automatos* 'self-acting'. One may define automation as the use of machines and computers that can operate without the need of human control. The term automation is often mentioned without any specific definition. For some people, automation means programming a programmable controller (PLC). For others, it is an automatic control of a unit process or a Supervisory Control and Data Acquisition system. Still for others, it means that some information is presented on a screen. From the simplest to the most complex application, automation is present in many forms in our daily life. Household thermostats are simple examples, while mobile telephones are much more complex. Soon we will see self-driving cars that are in the frontline of advanced automation. Automation is a hidden technology in the sense that it seems that we do not notice it when it works. It is only observed when it does not work.

The author claims that the human is still the most important part of automation. The paradox of automation says that the more efficient the automated system is, the more crucial the human contribution of the operators will be. Bainbridge (1983), a cognitive psychologist, discussed the ways in which automation of industrial processes may expand rather than eliminate difficulties for the human operator. Humans are less involved, but their involvement becomes more critical. If an automated system has an error, it will multiply that error until it is fixed, or the system is shut down. This also will require that both designers and operators need to acquire a new and more multifaceted way of thinking.

Automation systems relate to many disciplines, which probably is the reason why there are so many different definitions of automation. Each professional will see the automation challenge from his own platform and experience. Therefore, it is easy to get confused by the very size of the topic. Is it relevant to call *automation* a scientific discipline? Maybe the most important feature of automation is the fact that many different disciplines must be combined, but in a scientific way, to achieve a functioning system. Another attractive feature of automation is that the same methodological tools, developed in *system theory*, can be used in many diverse fields, from automotive, to aviation, chemical industry, and environmental processes.

Automation looks like a 'decathlon' in science and engineering and may combine:

1. *Measurements*: sensor and instrumentation technology,
2. Communication technology,
3. Signal analysis and processing, mathematical statistics,
4. Database technology and software engineering,

5. Control engineering,
6. Optimization theory,
7. Real-time computer systems,
8. *Process technology, dynamic modelling and simulation*: microbiology, water chemistry, chemical and biological process technology, reactor technology, hydraulics, etc.
9. *Actuators*: power electronics, electric drive systems, valve technology, and
10. Human–machine interaction.

An individual specialist in any of these areas cannot usually solve a large automation challenge alone. It requires close cooperation between people, as well as an integrated view of all the various methods, processes, tools, and methods that must be utilized. Here, we try to show how the various areas can be combined in a systematic way. Maybe the biggest challenge is to formulate the goal of the automation task. Often there are contradictory goals that must be weighed against each other. When this is done, the task remains to recognize available methods and theories to solve the problem. Three aspects of automation in the urban water cycle system are emphasized here: uncertainty, feedback, and complexity.

Uncertainty

Uncertainty in the process or in the environment around the process is a primary motivation for automation. In a process industry (including the water industry), a control engineer is frequently faced with two challenges from his non-control colleagues. The *process design* engineer asks why control is needed. 'We can design the reactor so that the output quality is always satisfactory, so why do I need control?' The *operations* engineer asks why the control is not perfect. 'That controller is faulty! The concentration is cycling continuously'.

The first challenge can be easily explained: the equipment will not stay exactly as it was designed; the external load will vary, or the supply services (air flow, chemical dosage, etc.) will not always be constant. On top of this, there are equipment disturbances like breakdowns or sticky valves. The start-up phase is different from the continuous operation.

The second challenge can be trickier to answer: it may be a nasty system to control. The gain may be nonlinear which indicates that the process – its time behaviour and its sensitivity – behaves differently at low loads and at high loads. For example, the hydraulic behaviour in a pipe may change with time as the pipe surface is coated with scale. There may be a large dead time, which means that the response from a sensor is delayed, or that the result of a control action cannot be seen until after a certain time period. The control action is usually constrained: a valve cannot open more than 100% and the flow rate cannot be negative or beyond the pump rating.

Disturbances are everywhere and are the main reason for control. Below we will discuss major disturbances in the urban water supply system. No measurement is perfect, so the information we get must be taken with a grain of salt. The amplitude may be biased because the instrument is not properly calibrated. The signal may vary because of internal noise in the sensor. Also, the process itself is subject to disturbances. There is a whole branch of mathematical statistics that has been developed to deal with this kind of problem.

Feedback

A feedback loop has the purpose to get a system to behave in a desired manner despite disturbances. A controller senses the behaviour of a system, compares it against a desired response (goal), computes corrective actions, and actuates the system to realize the desired change. This basic *feedback loop* of sensing, computation, and actuation is the central concept in control (Figure 1).

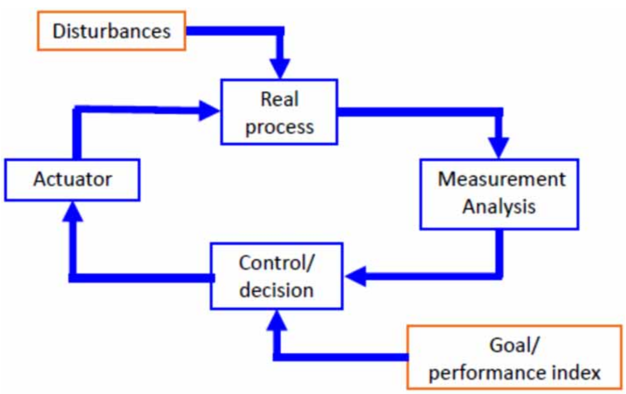


Figure 1 | The feedback principle.

Feedback is the heart of control and automation. We use feedback more or less conscientiously every minute of our life. Information from our feet and our balancing sensors is processed to our muscles to keep us walking or standing. Oxygen levels in the blood stream are fed back to our respiratory system to keep us going. Driving a car involves a great deal of feedback. The 'purpose' is to keep the car along the road and to avoid obstacles. The driver ensures that the car position and speed are within given limits. The eyes watch the instruments and the surrounding area and look for changes or 'disturbances'. They require that the speed or direction will be corrected all the time. The brain processes the 'measurement' data and decides how to change speed and direction. The decision ('control signal') is transferred to muscles ('actuators') that will turn the steering wheel or the accelerator. A good driver also looks ahead and can detect an obstacle well ahead and will correct the speed or direction to avoid a problem. This is called *feedforward*.

Feedback control is a powerful tool. It makes it possible to attenuate the impact of disturbances and process variations. It can transform poorly performing components into good systems, and it can stabilize unstable systems. In other words, the purpose of control is to get a system to behave in a desired manner despite disturbances.

Sometimes, a disturbance can be measured before it enters the plant. Then the information can be *fed forward* to prepare the plant. For example, a quality measurement in the water source is forwarded to the pumping system into the treatment plant. To make a correction before it hits the plant typically requires a model that, however, is seldom perfect. Therefore, it is mostly recommended to combine feedforward with feedback. The former realizes an early correction while the latter ensures precision, that the goal is reached.

Sometimes the controller is automatic, as in most equipment. Sometimes a controller is a human being, as in management decisions. Simple systems only require a single feedback loop, and the desired performance seems to be straightforward. Quite often, however, compromises must be made, for example, to suppress noise in signals but still recognize and reject disturbances in an efficient way. In more complex cases, performance must be monitored and evaluated so that a learning process can be initiated. In this context, machine learning and AI are providing the tools for learning, so that a control system may improve its performance based on its past recordings. Bernardelli *et al.* (2020) describe how machine learning is applied for wastewater treatment. In an IWA White Paper, Kapelan *et al.* (2020) describe AI-based solutions for the water sector.

Controlling a process can be defined as either keeping the process at its current state or changing the process from one state to another. Keeping a process at a desired state despite disturbances is the most common form of control in water systems. Moving a process from one state to another is called state-driving, which may be necessary to bring a process from an undesired performance to a safer operation. Defining a proper goal (performance index) is crucial, i.e. assessing the consequences of the control action. Depending on the chosen performance index, the resulting operation may vary dramatically.

The measurement task is a matter of instrumentation and the actuator task a matter of realizing a decision into a physical force, movement, or torque, using actuators like electric motors or pneumatic valves. The control algorithm can vary from a simple on-off algorithm with a single input and single output to a complex system with many inputs and outputs. In most unit processes of water systems, the control algorithms are relatively simple. The challenge increases when operations are to be integrated.

The principles of feedback and feedforward control are applicable all the way up to high-level strategic decisions. The framework is always the same, whereas the measurements, the analyses, and the decisions are different. Hence, it is vital to understand this way of thinking for utilities to become smarter, more robust, resilient, efficient, effective, and most importantly, more sustainable (Ingildsen & Olsson 2016).

Complexity

While the technology for individual processes and computer systems has developed tremendously, there is still an incomplete picture of system aspects of the combination and coordination of all processes and components into an integrated urban water supply system. This includes disturbance monitoring and handling in different parts of the system, coordination of actions to handle large short-term or long-term disturbances. The system aspects become complex due to uncertainties and disturbances, huge amounts of data, many levels for decision, and a wide span of time scales. Challenges become even more evident, if decisions – automatic or manual – must be quick, requiring sufficiently complete information. Automation should deal with the *combination* of flows of information, material, and energy in the water system.

Figure 2 illustrates key parts of the information flow in an automated system. All of them are included in a feedback loop. In principle, all parts can be either automatic or manual. Measurement can also appear as observations, communication may be handled by humans or various physical communication channels, control may be executed as automatic or human decisions, and the actuators can be machines or human intervention.

Automation is a critical tool to adapt to the complexity of real water and environmental problems. These are often 'wicked' – they have no clear definition of the problem and the solutions are mostly unknown and changing.

OBSERVING THE WATER SYSTEM

To measure is to know. External disturbances to the water cycle can often be measured, which provides early warning to system operations. Some disturbances can also be attenuated by proper automatic control actions.

Measurements

Adequate instrumentation is a basic precondition for control. In water systems, it is apparent that flow rates and a multitude of concentrations and quality parameters are the foundation for all operations. The instrumentation must be robust, easy to maintain, and cost-effective. This is even more important in an unmanned process.

Sensors and instrumentation have improved considerably during recent decades, but still there are sensor limitations, especially to monitor and protect water quality online. There is a development towards 'smart' sensors with multiple heads, which can be placed anywhere in the processes. The introduction of a sensor in a plant or system requires not only confidence in the equipment. If the value of the measurement is not considered beneficial, then it is too easy to lose interest in the sensor. Then, the performance of the measurement will gradually decrease because of lack of attention or maintenance. Too many high-quality instruments have failed because of this lack of connection with the purpose of the information. Further, water managers may be more prepared to support investment costs rather than maintenance costs. This attitude should be challenged since poor maintenance results not only in poor performance but eventually in the loss of invested money.

Before we even consider controlling the water quality, it must be ensured that plant equipment is working adequately. If any operating failure is noted, an automatic

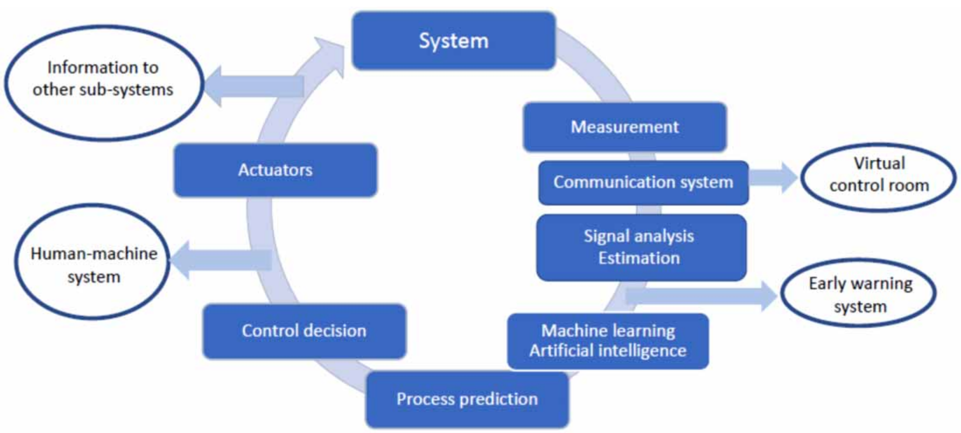


Figure 2 | Illustration of activities included in the automation process.

alarm should be sent to the operating personnel. This includes meters of electric motor speeds, acoustic noise measurements, and indicators that can ensure that pumps are running. Simple level measurements or hydraulic measurement sensors can confirm that tank levels and flow rates are within acceptable limits. Emphasizing the importance of 'keeping the plant running' is *not* to obtain accurate information of the plant state, but to ensure consistent basic operations.

Key measurements in water supply systems are:

- *Hydraulic measurements*: distribution system parameters, customer use, flow rates, water levels, stormwater levels, and pressure.
- *Drinking water quality measurements*: turbidity, free chlorine, pH, organic matter content, UV254/total organic carbon, oxidation/reduction potential, conductivity, temperature, colour, and ozone. Other essential measurements are pathogens, disinfection by-products (carcinogenic), and chemicals of emerging concern.
- *Bodies of water*: quality and hydraulic measurements in rivers, lakes, wetlands, and reservoirs.

It is anticipated that low-cost devices will soon be available to monitor the transmittance, total suspended solids, particle size and particle size distribution, and turbidity as well as selected organic and inorganic chemical constituents. Capodaglio (2017a) has reviewed existing and expected online monitoring for the measurement of pollutants in water. Chemosensors, as an alternative to traditional analysers, can supply measurement values in real time. Biosensors offer a promising basis for providing information about water quality. There has been progress for measuring pathogenic bacteria, while biosensors for viruses and fungi are still quite a challenge. Further details of sensor properties are found both at vendor websites (search for 'water and wastewater sensors' and similar keywords) and in Ingildsen & Olsson (2016).

Some reflections on digitalization

Digitalization is sometimes described as a new phenomenon. However, automation has been a major part of the digitalization story and started in the 1970s when equipment and processes were becoming computer controlled. In recent years, digitalization has incorporated business operations. Thus, people, beside engineering, have been impacted, creating much more attention to the development. Personnel, utility organization, decision-makers, as well as customers will be influenced by digitalization. It boils down to achieving informed decisions for the utility as well as for the customer (Vanrolleghem 2019).

Industry 4.0, or the fourth industrial revolution, is the collective term for technologies and concepts within automation, process industry IT, and manufacturing technology. The concept includes enabling technologies such as IoT, cloud computing, and machine learning. It implies that every product or process part carries information, so that the plant can organize itself when properly connected to the other units in the net. Two developments in parallel will make the water industry immensely data rich: low-cost sensors as part of IoT, and Information and Communication Technologies that form the infrastructural foundation for innovative technologies.

Urban water cycle operations should be more integrated, requiring both water quantity and quality models. Energy and mass balances are needed for the urban water supply cycle, from water abstraction, treatment, and distribution to consumer behaviour. The ability to collect information and communicate it from remote devices and correlate that information across diverse systems will help us achieve near-real-time models for prediction and warning. The need for ensuring data quality will be even more emphasized. What to measure and where to measure it should be topics for much needed research.

Monitoring – detection of system anomalies

Monitoring indicates tracking the operational state of a process or a machine via online instrumentation (Figure 3). By analysing measurement data, the detection time of anomalies can be shortened, for example for leakages, component failures, or water thefts. This will reduce water loss, contamination, or energy waste (Mounce *et al.* 2010; Yuan *et al.* 2019). Monitoring as a basis for early warning in water systems is described in literally hundreds of papers. Overviews are found in Irizar *et al.* (2008), Hamouda *et al.* (2009), Olsson *et al.* (2014), and Corominas *et al.* (2018).

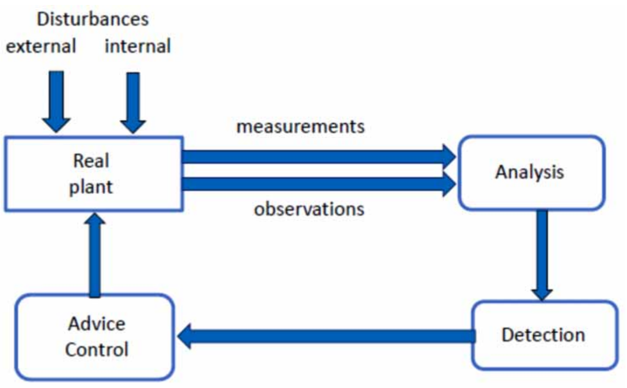


Figure 3 | A monitoring system is based on analysis of measurements and observations. A fault or failure can often be detected automatically. Based on the result, some advice or operator support can be given, and a control action can take place.

Any monitoring system must determine whether acquired data are meaningful and correct, which makes data screening essential. As a minimum it should include normal range comparisons (high and low limits), rate of change, and variance. Low-pass filtering techniques are essential to remove noise while retaining the essential signal information. High-pass filters can detect sudden or fast changes. More sophisticated monitoring techniques rely on AI tools, e.g. by comparing the observed behaviour with 'typical' patterns of similar units. Tinelli & Juran (2019) applied AI monitoring for early chemical and/or bio-contamination detection.

Monitoring can also be achieved by using dynamic simulation, utilizing real-time data from multiple sources, so called digital twins. The idea is not at all new and was applied in nuclear reactor control already in the 1990s to guide operators before any movements of control rods in the core were performed. Even if digital twins are promising tools for online decision-making, there is still much development needed to handle model complexity, uncertainty, and data requirements.

Several books and articles on elementary data analysis are freely downloadable from the Internet (search for 'data analysis', 'statistical data analysis', and 'data mining'). There is a lot of freely available as well as commercial software for data analysis. Software like Excel is useful for elementary data analysis, while software products like Matlab (http://se.mathworks.com/), SAS (http://www.sas.com), and SPSS (https://www.ibm.com/analytics) contain a multitude of statistics and data analysis methods. R is a popular, open-source software environment for statistical computing and graphics (https://www.r-project.org/). Python is a fully functional, open, interpreted programming language. Various packages can be easily installed in Python, making it practical as statistics software. Python is particularly suited to the Deep Learning and Machine Learning fields (https://www.python.org/). Naturally, the true benefit is harvested when these methods are applied online.

HANDLING DISTURBANCES

All infrastructure systems are subject to external disturbances. A water supply utility cannot control customer behaviour. Water quality in water extraction may change. Many disturbances have been considered non-controllable. However, this is no longer true, and many disturbances can at least be attenuated by design or by automation and control. From an automation perspective, we consider two aspects of external disturbances:

- *Early warning*: Measuring the disturbance in terms of flow rate and concentrations. Automatic signal analysis and estimation can offer early warning and can feed forward this information to the control of processes downstream.
- *Control*: Some disturbances can be manipulated and at least partly attenuated so that the processes downstream are less perturbated.

How do we prepare for disturbances using flexible design? How do we design in a modular fashion – to adapt for increasing demands for the future – and still have control and automation in mind? The ability to handle disturbances must be considered, and the relation between plant design and operation cannot be neglected. The design cannot be based on only steady-state considerations. Dynamic behaviour must be considered. Unfortunately, there is still a lack of understanding between control engineers and design engineers.

Automation becomes particularly important in time scales that are too slow or too fast compared with time scales that humans can handle more readily. Some disturbances and changes are gradual and develop over a long time. They can grow unnoticed for the human observer until they suddenly reach a critical level. Examples include slow composition changes of harmful components in a drinking water source, and asset management, where wear-and-tear can develop unobserved over a long time. Automation should be applied to continuously monitor deterioration in pipe walls, too much friction in valves, wear of machines, etc. Continuous automatic monitoring of slow development increases the chances of early detection.

Sudden disturbances can be too fast to be easily detected by a human operator, like a burst in a water pipe. Automation helps humans to consistently look for small changes.

Raw water extraction – drinking water treatment

A centralized water supply system is a complex infrastructure, requiring large investments, so there are obvious incentives optimizing the operation. This includes energy savings, early detection of raw water quality changes, detection and localization of leaks and bursts, and satisfying user demands. Increasing water scarcity is another apparent driving force.

The automation of drinking water treatment plants (DWTPs) has attracted attention in recent decades (Olsson *et al.* 2003). In the beginning, the goal was to operate the DWTPs to mimic human operators. The development has shifted to make the control and operation driven by the current state of the system, using feedback and feedforward control.

Control methods for DWTP were developed by van Schagen *et al.* (2010), emphasizing disturbance identification and using feedback to attenuate the disturbances. The resulting chemical usage in the softening treatment step could be decreased by 15%. A key feature of the control is to recognize the dynamical changes rather than base the operation on steady-state considerations.

Drinking water treatment depends, to a large extent, on coagulation followed by separation. The global cost for coagulants is formidable, motivating control of coagulant dosing (Dentel 1991; Ratnaweera 2014; Ratnaweera & Fettig 2015). Typically, a dosage control system measures turbidity, pH, conductivity, and temperature of the feedwater. By modelling how the variables relate to the amount of dosage, a feedforward control can be developed. By measuring key variables like pH, turbidity, floc size, and shape of the coagulant-dosed water, a feedback structure is created. Liu & Ratnaweera (2016) and Wei & Ratnaweera (2016) demonstrate the importance that feedforward should always be combined with feedback.

Kim van Schagen gives a comprehensive review of water supply control issues in Yuan *et al.* (2019). The use of soft sensors is increasingly important in estimating water quality. Soft sensors are computer models that calculate estimates of the water quality calculated based on physical measurements such as pressure, flow, and valve position, redox and conductivity, and accurate models.

A key feature of control is to recognize the dynamical changes rather than basing the operation on steady-state considerations (Bakker *et al.* 2003). Traditionally, customer consumption is reflected in the water level at the DWTP and the production is governed by level-based control. However, by predicting the water consumption for the next 24 or 48 h, the production rate of the DWTP can be adjusted so that the variability is minimized. This, in turn, will improve both the water quality and the energy efficiency (Bakker *et al.* 2013).

Pressure control in water distribution systems

Pumping operations are critical parts of a distribution system, and pump control and optimization has been studied for many years. Consider a district metering area where one pump (or water tower) at the head end will provide the flow rate and the necessary pressure. The pressure along the distribution pipes varies with the elevation and with the consumption along the pipe. The pressure must be sufficiently high for any customer, and the most remote customer typically represents the *critical pressure point*. When consumption is high, the pressure will drop faster along the pipe. To satisfy the critical point, the pressure at the head end must be sufficiently high. Consequently, the pressure is typically higher than necessary for customers far from the critical point. Traditionally, pressure reducing valves will modify the pressure. During low consumption in the night the pressure reduction along the pipe is much less, so the critical pressure will increase. Thus, the pressure in the critical point can vary significantly during a diurnal period.

There are several shortcomings of traditional pressure control. Firstly, excess pressure costs energy. Secondly, large pressure variations cause mechanical wear of the pipes, increasing the probability for leakages and bursts. Thirdly, once a leakage has occurred, a higher pressure will result in more water being lost. This motivates accurate pressure control.

Advanced pressure control should guarantee that the critical pressure is maintained all around the clock. This is often controlled with pressure reducing valves along the pipe, but every valve is causing energy loss. Instead, the pressure should be managed by pressure booster devices along the pipe. Variable speed control for pumps and compressors should be the standard equipment choice for better controllability as well as for higher energy efficiency. There are commercially available control systems for this kind of pressure management (Grundfos 2020). Thus, the pressure can be kept just above the minimum requirement, saving energy, reducing the risks for leaking (Filho *et al.* 2018). The pumping must be based on real-time measurement and control. To achieve more advanced pressure control, the statistics of daily variations can serve as a baseline for the control computations. Yuan *et al.* (2019) give an overview of optimization algorithms.

Advanced control of the water distribution system will result in large savings, as demonstrated by Ganidi & Holden (2014) and Page *et al.* (2017). One of the challenges is to apply a relevant prediction horizon for the control. Ganidi & Holden found that a 3-h prediction period gave a better performance than a 12-h horizon. This requires that data processing be sufficiently fast.

Leakage detection

Traditionally, leak detection has been based either on data outside the distribution network or data from sensors brought into the network at certain times. The development is to establish a permanent set of sensors in the distribution network. More pressure and flow rate sensors can be deployed in water distribution networks and be combined with smart water metering at the user location (Cardell-Oliver *et al.* 2016; Shiddiqi *et al.* 2017, 2018). A large number of techniques and methods have been developed not only to detect a sudden leakage (burst) or a slow leakage but also to find the location of the leakage, both in a single-pipe system and in a distribution network (Misiunas *et al.* 2005). Overviews of current technologies for burst detection and leakage management are found in Puust *et al.* (2010), Romano *et al.* (2014), and in the keynote by Savić (2017). As described above, the probability for leakages will decrease with appropriate pressure control.

CUSTOMER BEHAVIOUR

The electric power costs for water supply, dominated by pumping energy, are around 80% of the costs for water treatment and distribution. However, a major part of the energy cost is related to the customer use, where most of the energy is spent for water heating. Statistics as well as basic energy balances show that more than 90% of water-related energy in the urban water cycle is used at home (Reffold *et al.* 2008; Kenway *et al.* 2011; Olsson 2015; Kenway *et al.* 2019). Water heating will require around 30–50 kWh/m^3 which is 1–2 orders of magnitude larger than the energy for (cold) drinking water delivery and wastewater treatment. Whatever the energy source used for water heating – natural gas, solid waste incineration, or electricity – there are obvious incentives to save user energy use. There is an increasing interest in heat recovery from used water, by using heat pumps where there is a need for the heating, or by recovering heat from household consumption in showers, washing machines, etc. The energy use motivates the effort to influence customers and their water use.

For a long time, utilities have encouraged or subsidized water saving equipment like shower heads, faucets, toilets, washing machines, and dishwashers. Smart water meters, connected to a wireless network, will make the water use decrease by between 2.5 and 29% in various locations (Sønderlund *et al.* 2016). Incentives for using metering will increase along with water scarcity. Thames Water supplies water to 3.3 million properties in the London area. The utility has an ambitious smart metering installation programme and aims to have metered 100% of connections across the region by 2030. Presently, around one-third of the customers have meters installed, and they use around 12% less on average compared with the customers without individual metering (Thames Water 2020).

There are ways to indirectly control water consumption, by real-time information, and by tariff structure (Liu *et al.* 2017). Automatic water measurement can be supplemented with real-time information to the customer. 'Your water use last week was 20% higher than average' and similar messages. The tariff structure should not be underestimated. If the fixed cost makes up the biggest part of the total cost, it does not give an incentive to save water. Massive subsidies occur in both low-income and high-income regions, which lead to serious under-valuing and severe misuse by individuals and industry. Yet, there is a need to ensure that every human will have the right to get clean water. Therefore, water pricing needs to be revised in many places and countries. The closer the price of water approaches full cost the better water could be valued. Many places charge the water so that even the poorest people can afford a minimum amount of water use, the most valuable water that life depends on. Anything above this level should be priced according to the real costs it takes to make the water drinkable. To water a lawn in a water-scarce area is not a human right and should be charged accordingly. Simply expressed, we should pay less for the necessary water need and more for the 'luxury' needs, as qualitatively illustrated in Figure 4.

Some regions have recognized that the tariff should encourage efficient use of the water and have already implemented a tariff structure inspired by Figure 4 (Olsson 2015).

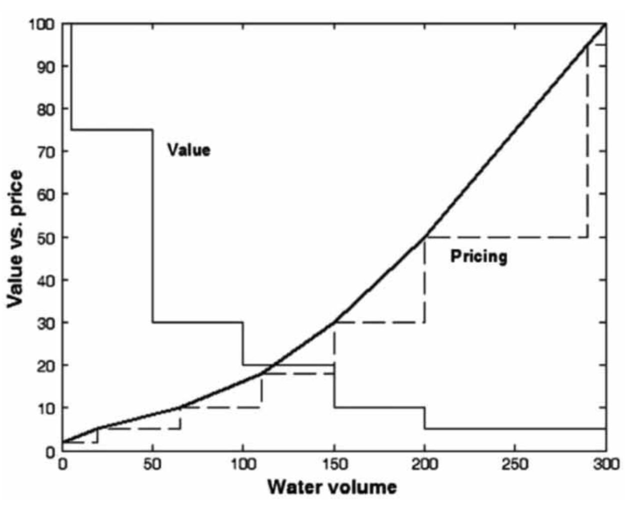


Figure 4 | The perceived value of water compared with a structure of the tariffs (from Olsson 2015).

WASTEWATER TREATMENT AND WATER REUSE

Dynamic modelling, control, and automation in sewer networks and wastewater treatment plants have been applied for many decades and have been far more extensive than in water supply systems. This has been visibly demonstrated at the 12 IWA-ICA conferences between 1973 and 2017, summarized in Olsson (2012) and Olsson *et al.* (2014).

Wastewater treatment control

Most conventional control systems are unit process oriented with the aim to enhance the treatment performance leading to consistent effluent quality, reduced energy, and chemical consumption. There is an increasing ambition to take the coupling between different process units into consideration with the aim to achieve plant-wide control. In some cases, also the entire system of sewers and treatment plants has been considered. A discussion of automation in wastewater treatment systems is outside the scope of this paper, and comprehensive reviews of these control systems can be found in Olsson & Newell (1999), Olsson *et al.* (2005, 2014), Olsson (2012), Åmand *et al.* (2013, 2014), and Olsson & Ingildsen (2020). Wastewater treatment, however, is gradually more coupled 'backwards' to water supply as water reuse is increasing. This requires more attention devoted to automation in processes that are following a typical wastewater treatment facility, such as advanced oxidation, granular carbon adsorption, ultrafiltration, and reverse osmosis.

Water reuse

With increasing water scarcity, water reuse offers a possible supplementary water supply. Water sources for potential reuse include municipal wastewater, industrial process and cooling waters, stormwater, agriculture runoff and return flows, and produced water from natural resource extraction activities. These sources of water should be adequately treated to meet 'fit-for-purpose specifications' for a particular use. This creates an obvious challenge for automation, to guarantee that the right water source connects to the proper use.

Stormwater harvesting offers a real possibility. This opportunity is illustrated by a city where sewer overflow is common. When heavy rain hits the region, the stormwater from one suburb to the central treatment plant will overload the sewers. One solution is to harvest the stormwater at the source and use it as industrial water, thus offering double reward: less water supply is needed and the risk for sewer overload is decreasing. The potential for automatic handling of stormwater is huge.

Singapore had the quest to create a more independent water supply already in the early 1960s. For around two decades, they have produced drinking water quality from treated effluent water to create their NEWater (www.pub.gov.sg/watersupply). Today, it provides 40% of the water supply. This portion will grow to 50% in 2030. To produce NEWater treated, used water is processed in three stages, microfiltration, reverse osmosis, and UV disinfection. In parallel with the technology progress, they had to create an acceptance of reused water. Singapore has led the way, by public events, by education, and by a world class testing. Already, in 2002, 98% of the Singaporeans accepted to drink NEWater.

The potential for reusing water is huge. In the USA, the EPA has estimated that less than 1% of all U.S. water use was satisfied by recycled water in 2020. Beijing is a water-scarce city with about 140 m^3/capita of water resources, which is one-eighth that of China and one-tenth that of the world average and is far below 10^3 m^3/capita (Fan *et al.* 2015) that is considered adequate. California has been hard hit by droughts and water scarcity and has a lot of reasons to expand water reuse. It is estimated (Ceres 2020) that as much as 3×10^9 m^3 of potentially reusable water is yet to be developed. This is about five times what the city of Los Angeles supplies per year to its customers. A new EU regulation on minimum requirements for water reuse for agricultural irrigation has entered into force (Helmecke *et al.* 2020). The new rules will apply 2023 and are expected to stimulate and facilitate water reuse in the EU. The reuse sector in the EU is still underdeveloped, with just 0.5% of the annual total freshwater extraction (1,100 Mm^3/year).

IWA considers used water to be 'one of the most under-exploited resources we have' (IWA 2018). About 80% of the world's wastewater is discharged into waterways, often partially or completely untreated. Water, as having a critical role in transitioning to the circular economy, includes decentralized solutions.

INTEGRATED SYSTEMS

Integrated management of the whole urban water cycle will be required in future urban areas. Water supply will come from multiple water sources: surface waters, reuse water, stormwater, groundwater, and seawater through both centralized and decentralized services. Fit-for-purpose water production will become more important, as different water uses do not necessarily require the same water quality. These strategies add another level of complexity to the already complex urban water system. All systems and components in the urban water cycle – from the water source to the receiving water – are interrelated parts of the water system.

An important consequence of automation has been demonstrated many times in industrial automation projects. Installing real-time control forces and encourages people from various sections of an industry or utility to share experiences of how to handle different levels of information. This opportunity is also offered in urban water systems. Information should be universally available for operation, from the water intake to the effluent into the receiving water. Disturbance handling is one apparent reason. Energy optimization and resource recovery are other reasons.

Integrated control of multiple sub-systems is still rare, except for combined sewer overflow control for the benefit of receiving water quality (Benedetti *et al.* 2013). Widening the perspective from single processes to plant-wide and further to the entire urban water cycle is necessary to handle the increasing complexity of urban water systems. Rodriguez-Roda *et al.* (2002) made a pioneering contribution to this school of thought. Hauser & Roedler (2015) present a general overview of what is needed in an integrated water system in terms of technological components and interactions that are needed for an interoperable solution. The structure is much inspired by the OSI (Open System Interconnection) model that is applied in industrial communication systems. Such a transition requires systems thinking, where the multitude of couplings between processes and individual controllers are considered (Beck 2005).

The connection to nature

Trust is a key resource of any personal or professional relationship. The values that drive the relationship between urban water use and nature are key to developing trust: 'can nature trust us?' As a sign of a new attitude to nature, Bolivia and Ecuador have passed laws granting all nature equal rights with humans. In Ecuador, the Constitution enshrines nature's 'right to integral respect'. In practice, that means that all persons, communities, peoples, and nations can demand that Ecuadorian authorities enforce the rights of nature. One of those rights, according to article 72, is the right to be restored. In New Zealand, a Maori tribe has successfully fought to have their Whanganui River – and ancestor – on the North Island given the same legal rights as a person. India's Ganges River was recently granted human rights (The Conversation 2019). The single idea is that there is not *we* and the *Earth*. It is *us*.

Automatic measurements and early warning systems are important tools to create a sustainable connection between the urban water system and nature. We should aim at measuring the quality of the water intake in real time, including indicator organisms as well as online measurements of the ecological state in the local environment.

In (digital) discussions at the Stockholm World Water week in 2020, it was noted that companies of all sizes experienced the same problem – they have more solutions than they can sell. If regulations would opt for greener solutions, there would develop a booming market for water-smart technology and a wave of new innovations. There are already plenty of solutions that would benefit humans and nature, but the business case for them is not there yet. There is an apparent failure where decision-makers do not know how to estimate the value of nature. We as water professionals must be better at explaining the role of water for humans and nature in terms that can translate this perspective to economic calculations.

DECENTRALIZED SYSTEMS

The decentralized approach to water supply, like groundwater pumping, decentralized stormwater harvesting, and local wastewater treatment and reuse, benefits from the advantages of source separation, which encourages simple small-scale systems and on-site reuse. Arguments in favour of decentralized wastewater management systems for communities in rural or peri-urban areas have been discussed and advocated by many (Wilderer & Schreff 2000; Parkinson & Tayler 2003; Libralato *et al.* 2011; Larsen *et al.* 2013; Olsson 2013; Capodaglio 2017b). Decentralization facilities can usually be built to exactly fulfil current needs, and be expanded later, as further needs arise.

Even in developed countries, cities are gradually losing their character of densely concentrated settlements and are gradually sprawling to the countryside. Since the cost for distribution or collection systems mostly is the dominating capital cost, decentralization is becoming a viable alternative. The technology for both drinking water treatment and water reuse is scalable, from household sizes and up. Furthermore, electric energy supply is also scalable and a reality today (Jones & Olsson 2017; Olsson 2018). These trends will rely on smart solutions using adequate sensors, control, and a reliable, affordable, and user-friendly automation.

Maybe the whole business model of decentralized water treatment will change. The user may not own the equipment and the responsibility of its operation and product quality is handed over to a business operator. We will buy water quantity and quality.

WATER AND ENERGY

Integrated urban water management could reach beyond water. The nexus of water and energy has been clearly identified (Olsson 2015). There is also a trend towards a hybrid structure involving electric power generation, water production, and wastewater treatment at both centralized and decentralized scales (Jones & Olsson 2017).

The development of renewable energy, primarily solar photovoltaic and wind power, is already dramatically changing the availability for electrical energy while contributing to decreasing the carbon footprint. Available electrical energy is a critical factor to pump or treat water. Access to electrical energy can be enjoyed by 84% of the global population, implying that almost 1.2 billion (10^9) people are still without it. Renewable energy technologies are already making a major contribution to universal access to carbon-free energy. The world now adds more renewable power capacity annually than it adds (net) from all fossil fuels combined (IRENA 2020).

In many regions of the world with energy poverty, there are abundant renewable energy sources. Solar and wind power offer huge opportunities in off-grid electricity systems. Small-scale off-grid systems have the potential to improve energy access in rural and peri-urban parts of the developing world, by providing not only lighting and heating but also pumping to gain access to water as well as water reuse and purification using different technologies including biological treatment and reverse osmosis. Already solar power in small-scale installations has provided electrical power and lifted millions of people out of poverty. Renewable energy offers new possibilities because of its scalability. It can deliver energy for all sizes of water operations, from the household level to the village or urban community level, from the kW range to several hundred MWs. The possibilities for clean water production using renewable energy in combination with automation are explored in Olsson (2018), available online.

LOOKING INTO THE FUTURE

Speculation about future often gives us a laugh when we read it again a few years later. Hindsight is easy, and it can be useful, but guess work about the future takes us forward. Back in the 1990s, Bob Newell and I speculated about wastewater treatment in 2020 (Olsson & Newell 1999, Chapter 25):

- *Holistic systems*: the wastewater water industry in 2020 will become just a part of a 'water industry', an industry concerned with all aspects of the resource we call 'water'. Still we will treat the whole urban water cycle as one system.
- *Full cost recovery*: by 2020, the users of water will pay what it costs. No hidden subsidies from our taxes. Only then will we all appreciate water as much as those who struggle to survive in arid lands. Water tariffs are very strange in many places and do not reflect the real value of water.
- *Zero dry weather discharge*: in dry weather, the water system will be almost a 'closed system'. That is, complete recycling of treated wastewater, no explicit discharges to receiving waters, and only requiring freshwater makeup to account for leaks in the distribution system. Wet weather untreated bypassing will not exist.
- *Normally unmanned plants*: the Quality Team will visit maybe once a week, probably when the maintenance team visits. Monitoring and control will be automatic with adjustments made remotely. Perhaps, the laptop and modem already used at a few plants will even be replaced by the home 'Internet TV'.
- *Centralized Quality Teams and systems groups*: our Quality Team will now look after 10 or maybe even 20 plants. The systems group will probably be even more centralized, probably just one for the complete urban water system or even responsible for several complete systems. Routine operations are automated.

Some of these dreams from more than two decades ago still need to be a reality. It is my genuine belief that automation can be a tool to realize some of these goals. For example:

- *Instrumentation*: there will be a whole range of low-cost sensors and we should automatically measure and estimate the state of the whole urban water cycle.
- *Communication*: systems like IoT will connect thousands of sensors and 'soft' information in the urban water systems. Consequently, *cyber security* will be an increasing threat, and water utilities as well as other critical infrastructure organizations will need to build resilience related to cyber security. The current trend of remote workforce and remote operations is further adding to the cyber-risk challenge.
- *Data management, reconciliation, and analysis*: of huge amounts of data: soft sensors are natural parts of the system. However, it is worth mentioning that many tools have already been available for decades, but with different names, such as black box modelling (like process identification, ARMAX models, and artificial neural networks), grey box modelling (where process knowledge is required), as well as machine learning. Computing power will not be the obstacle, but rather our ability to interpret and condense data into useful information.
- *Automatic detection*: should be a routine task and effective AI algorithms should help us to provide early detection and *diagnosis* of external events as well as internal equipment faults. Finding effective *diagnosis* tools will require a considerable effort. More frequent

extreme weather events will require early warning systems to handle extreme conditions. This also means an integrated view of the urban system, both on the water supply side and the used water collection and treatment side.

- *Renewable energy, primarily solar, and wind*: will be utilized much more for water operations, not only in areas outside the power grid but also for decentralized water operations in peri-urban areas.
- *New processes*: are developed to handle various industrial and pharmaceutical micropollutants using specialized biomass. This opens for decentralized processes for water treatment and resource recovery. We will no longer require one water quality for all, but a water quality related to the water use. We will apply much more water reuse.
- *Sustainability*: we will have a better handling of sustainability with our systems in harmony with nature. I should aim at a metric to judge the sustainability of different options that will facilitate a fruitful dialogue between those involved: politicians, ecologists, engineers, and economists.
- *Integrated design taking operation into consideration*: today, we see good examples where design is complemented with dynamical simulations. This should be the normal plant design procedure. The trade-off between excess volumes and more control authority in manipulated variables is an issue that must be faced in the design. We stated this 25 years ago and it is still an important issue.
- *Education*: an increasingly sophisticated water industry will compete with the mainstream process industries for process engineers and process systems engineers.

It is not sufficient to make the water systems smart; we must be smarter water users. And still true 25 years into the future: water is life, and we must treat it wisely. The challenge from 1998 may still be valid: 'Our societies will need clean water and clean air. Sustainability will not only be a matter of cost. In fact, it is already a matter of survival in some countries. What role will automation play in this development and how can we meet that challenge?' (Olsson & Newell 1998).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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