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REAL-TIME CONTROL OF URBAN DRAINAGE SYSTEMS

The state-of-the-art

By

IAWPRC Task Group on Real-Time Control of Urban Drainage Systems

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Abbreviations Used

A/D	– Analog/digital
AI	– Analog input
AO	– Analog output
BOD	– Biochemical oxygen demand
COD	– Chemical oxygen demand
CSO	– Combined sewer overflow
CSS	– Combined sewer system
D	– Dead band
D/A	– Digital/analog
DDC	– Direct digital control
DI	– Digital input
DMWD	– Detroit Metro Water Department
DO	– Digital output
DWO	– Dry weather outlet
EPROM	– Erasable programmable read only memory
h	– Hysteresis
I/O	– Input/output
LED	– Light emission diode
LPP	– Linear programming problem
O&M	– Operation and maintenance
P-controller	– Proportional controller
PD-controller	– Proportional differential controller
PI-controller	– Proportional integral controller
PID-controller	– Proportional, integral, differential controller
PLC	– Programmable logic controller
RAM	– Random access memory
RTC	– Real-time control
RTCS	– Real-time control system
SWO	– Storm water outlet
UDS	– Urban drainage system
VLSI	– Very large scale integration

Preface

THE planning, design and operation of urban drainage systems (UDS) is a domain of civil engineers. Whereas technical progress in planning and design was strongly stimulated by research and development, the operational problems have received comparatively little attention.

Since an increasing number of UDS are equipped with sensors and data collection systems, knowledge is being gained of actual operational performance. Appropriate control systems (i.e. hardware) and control strategies (i.e. software) are being developed in order to use the existing systems better and to increase UDS performance to the maximum.

In 1986 the IAWPRC/IAHR Joint Committee on Urban Storm Drainage commissioned a group of engineers and scientists to study the technical developments in the field of real-time control of urban drainage systems (RTCUDS). Initially the task group focused on the compilation of the present knowledge on RTCUDS. The result is this state-of-the-art report. It is planned to keep the report up-to-date and, ultimately, extend it so that it can be used as a RTCUDS planning, design and operations handbook.

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1. Summary, discussion and conclusions

Urban Drainage Management. The historical solution of the problems in designing, constructing, operating and managing urban drainage systems (UDS) is challenged by real-time control (RTC). The limited efficiency in reducing flooding, environmental pollution and health hazards is caused by the lack of flexibility in the operation of the static UDS under dynamic loading.

A new concept of RTC is emerging to improve UDS performance and to reduce these hazards. A UDS (combined or separate) is operated in real time if process data currently monitored in the system are used to operate flow regulators during the actual process. The objective of this active operation of the UDS is to prevent flooding of the catchment and to prevent overflows to receiving waters before the capacity of existing storage is used up. At the same time, optimum flow rates to the treatment plant, depending on its capacity and operational state, are to be maintained.

By this means each particular storm and transient pollution load can be controlled using improved regulator devices and remote monitoring and control systems. RTC is essential for the full use of transport and storage capacities under all operational conditions. Without RTC a UDS can only work optimally for one loading, namely the design storm.

A number of obstacles to the use of this promising technique might hinder or even prevent the implementation of RTC, as follows:

- administrative boundaries within a physical UDS which constrain possible action within these political limits,
- separation of tasks (pollution control, drainage) in the operation of combined sewer systems, which are in fact two-purpose systems,
- funding arrangements that strongly favour high investment/ low maintenance solutions,
- inflexible UDS regulations and standards which prescribe static solutions,
- disregarding the potential of RTC for less costly design,
- the belief that RTC should solve all UDS problems immediately,
- the lack of a motivated management and engineering team, and
- the lack of skilled maintenance and operation crews.

Real-Time Control Concepts for Urban Drainage Systems. Real-time control assumes continuous monitoring and controlling of the flow process. In principle, the control of a process can be schematized to a simple control loop. This control loop requires a sensor to measure the process, a regulator to adjust the process and a controller to activate the regulator. Between these elements data have to be transmitted.

In RTC of UDS several hierarchic levels of control can be distinguished, i.e. local control, unit process control, global control and central management, with the latter being the top level. Depending on the requirements of a specific UDS, the control can be completely decentralized, fully centralized, or some mixed arrangement such as decentralized local control with central global control.

Distributed systems are most common in practice. They allow for local automatic control of the regulators and for central modification of the local control. Communication in a distributed system is usually realized by a telemetry network using public telephone lines. Global control can be executed manually (supervisory mode) or automatically (central automatic mode). It should be able to deal with all kinds of interference, be it malfunctioning hardware, communication system failure or on-site manual operation.

In a global control system a large amount of data has to be processed to supervise the day-to-day performance of the UDS as well as to check the effects of the applied control strategy.

Modelling the State of an Urban Drainage System. In the context of RTC the meaning of 'system' is the controllable part of the UDS. A real-time control system (RTCS) can be thoroughly planned if numerical simulation models are used. The following processes have to be modelled in order to obtain a comprehensive overview on the performance of the system:

- the input to the system,
- the system's response to the input,
- the total output to the environment, and
- the response of the environment to the output from the system.

Modelling of the input to the system is generally based on rain measurements, a surface runoff model and eventually a pipe routing model including wastewater and infiltration input. The sensitive part of the input modelling is the rain input, where phenomena like spatial distribution of rainfall, and growth, movement and decay of rain cells play a major role. So far, there are no models which incorporate these phenomena in a deterministic way. However, with a fairly dense network of rain gauges adequate rain input to a surface runoff model can be obtained. Another way of obtaining rain input data is the use of the radar technique which also provides a possibility of rain forecasting and a proper description of the spatial distribution of rainfall. The radar technique is operational in a few European and North American regions. Effort is being put into this field to make it more widely available for RTC in UDS. Pollution input to the system is more difficult to model and further work is necessary to establish a fair basis for this. Models for the state of the system, including modelling the input to the system, have been developed in great numbers for static, non-controllable systems. However, hardly any model has been described for the simulation of automatic regulators and external control input during the simulated process.

Hence, for the purpose of planning, analysing and operating real-time control systems there is a need for further development of models that include simulation of automatic regulators.

Pollution transport in the system is also a subject on which further work is needed in order to develop models which can simulate overflow pollutographs or treatment plant inflow loads. Presently no urban drainage models exist which also include simulation of the treatment plant. However, separate treatment plant models exist which, after coupling with an urban drainage quality model, could be used to simulate outflow from the treatment plant.

The impact of combined sewer system overflows, separate system discharges and effluents from treatment plants on the receiving water quality, can be modelled by some of the existing models for some parameters. However, their effect on the organisms living in the receiving waters is much more difficult to predict. Little is known on this subject, let alone applied in UDS management and operation.

Basic Control Techniques. Several types of control techniques are applicable in RTC of UDS, and closed loop control is the most common. Depending on the way control actions are executed and process signals are monitored, control systems can be divided into continuous and discrete control systems. For local control, continuous controllers can be applied as proportional (P)-controllers. In combination with a process with an integrator function, these systems act like first-order systems. The control performance can be improved by adding integrator (I) or differentiator (D) action to the controller. These so-called standard PID-controllers can be applied in many situations of RTC in UDS and can be adjusted in many ways to the different processes to be controlled.

Systems which already incorporate integrator functions, such as water storage, can very well be controlled by two-point controllers. To reduce switching frequency a three-point controller can be applied. High speed/low speed pumps in combination with three-point control is a typical example. Continuously speed-regulated pumps may use a PI- or a PID-controller as well.

In practice it is often very difficult to formulate the required control performance in advance, especially when the dynamics of the controller are concerned. Is a large deviation from the set point tolerable? If so, for how long? How often will it happen, etc?

In the design of a control system one has to rely heavily on experience gained in similar systems. If experience is lacking one has to examine the process dynamics by simulating the processes and the controller. Also functional considerations such as efficiency, safety, or operational life have to be considered. It is obvious that good collaboration between the control engineer and the process (UDS) engineer is important from the very beginning of the design.

Control Strategies. In a typical RTCS, pumps, sluice gates, weirs, etc., have to be operated to store wastewater and route it to treatment and receiving waters. The major objective in the operation of these regulators is to avoid flooding while minimizing combined sewer overflows (CSO) and operation and maintenance (O&M) cost. It is particularly undesirable to let flooding or CSO occur if the system has idle transport or storage capacities at the same time. Proper operation should ensure that this does not happen.

Neither static flow restrictors (e.g. orifices) nor locally controlled regulators (e.g. vortex valves, float-regulated gates) can guarantee good systems performance. This would only be achieved if each regulator (e.g. sluice gate) is operated according to the flow process in the whole system. This operational mode is termed global control. Global control allows flexible reaction with respect to every operational situation since the set points of the control loops can be continuously adjusted in accordance with the actual state of the entire UDS.

The time sequence of the set points of all regulators in a RTCS is termed control strategy. The determination of a control strategy can be either automatic or manual. The strategy can be found through mathematical optimization, search, decision matrices, control scenarios, trial-and-error (heuristically), or through a self-learning expert system. This can be done either during the ongoing flow process (on-line) or beforehand (off-line). After the control strategy has been defined it is executed by controllers which are usually distributed in the field at the regulator sites.

In most existing RTCS, operators adjust regulator set points based on their experience. This control mode is called supervisory control. It is flexible in that operators can use any kind of information that is available. They react flexibly in unusual situations and can discard control strategies that 'would not be successful anyway'.

The determination of a control strategy requires the specification of operational objectives, i.e. desired state of the system and priorities, and how to evaluate deviations from this target ('costs'). While this is mandatory for strategy optimization it is at least useful for other methods of finding a strategy. Problems arise since most of the operational objectives in a UDS are non-monetary, intangible, and/or conflicting and therefore difficult to define.

The decision variables in any control system are physically constrained by both capacity limits and the laws of water motion. Whereas the formulation of capacity constraints is fairly straightforward, the hydrodynamic constraints usually incorporate a simplification of the governing physical laws. The robustness of the control performance with respect to these simplifications has to be checked either by modelling the controlled process with a detailed (and more realistic) model or by careful 'fine-tuning' in the real UDS.

The better the inflow volumes and pollution loads are known in advance, the better the process can be controlled. It is desirable to know future inflows as accurately as possible for the whole control horizon. The control horizon is reached when the system is back to its desired (e.g. initial) state. In a UDS this control horizon is the remaining storm duration plus the time required to empty the system. Currently available rainfall and rainfall/runoff models may yield inflow forecasts which are considered to be not accurate enough. It has to be evaluated how inflow forecasting errors affect the quality of the optimized control strategy and, hence, in which cases inflow forecasts should be used.

Hardware Elements of Real-Time Control Systems. In a RTCS a large variety of hardware elements are applied for regulating, measuring or signalling purposes. Sensors applicable for RTC in UDS include rain gauges (e.g. drop counter, tipping bucket), weather radar, water level gauges (e.g. pressure probe, bubbler, sonic sensor), and flow gauges (e.g. level-flow transformation, electromagnetic, ultrasound, flumes). Sensors for pollutant parameters are not yet available for routine application in RTC of UDS. Very often limit switches (e.g. float, conductive, capacitive) are applied to support simple on/off control.

Regulators require careful design to withstand the hostile environment in UDS. These include pumps (e.g. radial, screw), weirs (e.g. perpendicular, side-spill, leaping), gates (e.g. sluice, knife, radial, sliding), valves (e.g. butterfly, plug), and fixed set point regulators. The latter do not require an external energy supply and have only limited flexibility with respect to global control systems since they do not allow the modification of set points.

The measured values have to be transmitted to a controlling unit and from there back to the regulators. In practice, digital communication between these units gives the best performance and enables the execution of more advanced control strategies.

UDS may cover a large geographical area and hence measurement, signalling and local control can be widely distributed. A telemetry network provides for the necessary communication facilities. Such a network collects all the data of the status of the RTCS to a central point. From there actions can be carried out manually or automatically to execute supervisory or automatic control strategies.

For local control, programmable devices are preferred, such as programmable logic controllers (PLC). They can be integrated in the telemetry network. The central unit is generally comprised of a telephone exchange unit and a subsequent process computer. Also the network often makes use of the public telephone system, which is used to couple central and local telemetry stations. Communication takes place by adapting the digital signals to the carrier medium (modulation) and is controlled by complex error checking protocols and data handling mechanisms.

The process computer offers the facilities for advanced operation of the UDS. Besides, complex control strategies can be developed in high-level software for overall control functions. The continuing developments in computer hardware and software and the decreasing price/performance ratio will ensure that in future the possibilities for overall control will be increased to a great extent.

Applications in industrialized countries of Western Europe, North America, and Japan show that RTC in UDS is rapidly evolving. It can be expected that in the future RTCS will be a common feature of a great number of UDS.

2. Urban drainage management

2.1 Physical and environmental aspects

2.1.1 ELEMENTS OF URBAN DRAINAGE SYSTEMS

In many European cities the UDS have been inherited from old cultures like the Roman Empire and only gradually extended. The basic tasks of all these systems are still the same, i.e. getting rid of all sanitary sewage and stormwater by considering an appropriate safety margin with respect to flooding and health hazards. On this basis civil engineers all over the world designed as many different collection systems and treatment plants as there are different perceptions about security and appropriate cost-effective solutions. Most of these systems have one common feature in that they are static, inflexible systems for which neither the connection of the drainage system with the treatment plant and the receiving waters, nor the possibility of temporarily activated storage has been considered. This is not state-of-the-art!

In the age of advanced technologies it was only a question of time until the idea of RTC of UDS was born. This happened concurrently with a change in mind towards environmental protection and with the necessity of minimizing the expenses in administrative budgets. RTC brings about:

- better use of storage instead of transport only,
- looking beyond the collection systems and drainage, towards the treatment plant, receiving waters, urbanization, pollution sources, and safety of sewer maintenance staff (Fig. 1),
- combining the necessity of lower investment costs and more operational efficiency, and
- using the capacity of all facilities of the UDS to master environmental and drainage problems in the service area.

2.1.2 PRINCIPLES OF URBAN DRAINAGE MANAGEMENT

Traditionally, the design of UDS was governed by the need to have reasonable flood protection. These systems, by definition, can only perform optimally in one case, namely, when

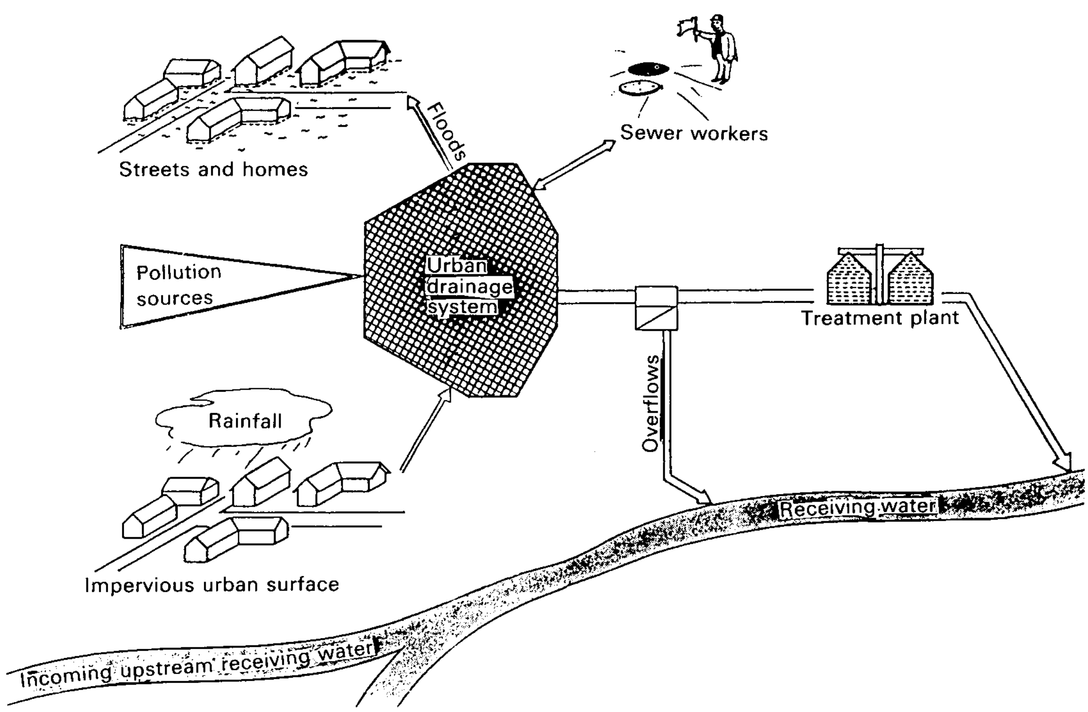


Fig. 1. Elements of urban drainage system.

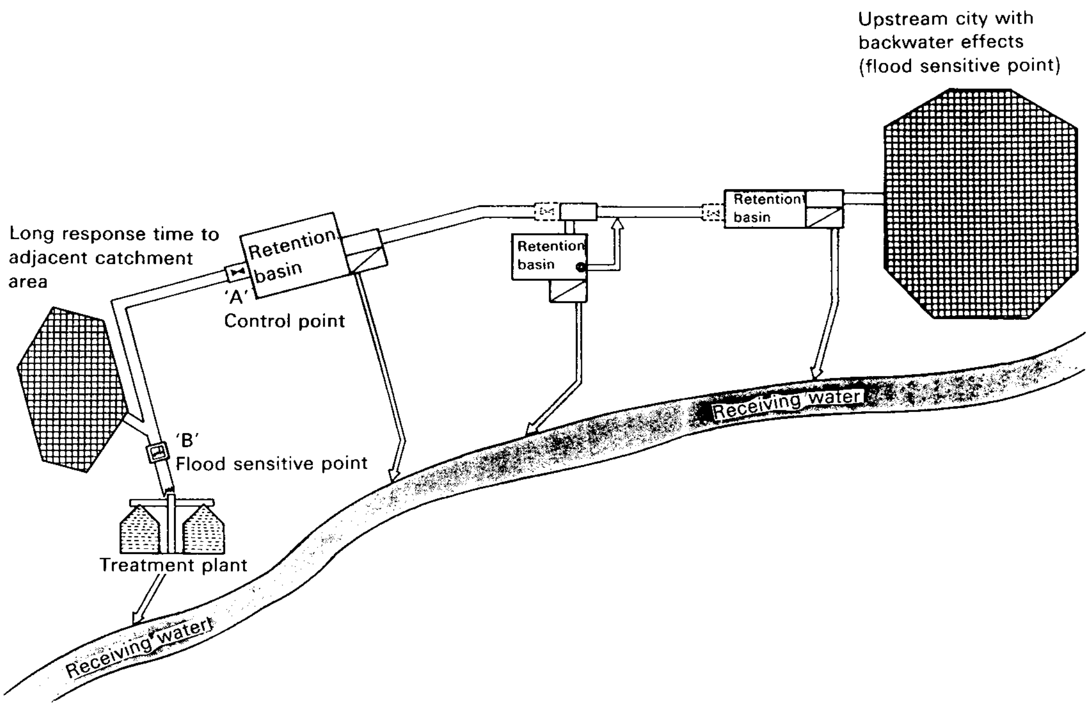


Fig. 2. Scheme of combined sewer network.

they are loaded with the design event, say, a spatially homogeneous 10-year storm of given duration. The consequences are:

- all except one storm are not distributed like the design event. Although they might not reach the depth of the design storm, allowable storm flow might be locally exceeded and floods might occur. Minor local storms might result in combined sewer overflows with negative impacts to the receiving water.
- the manager of a UDS assumes that no further action is needed since good care has been taken in the design of the drainage system.

If one is aware of how design methods may in some cases be inaccurate, how planned and actual drainage conditions differ due to urban development, how sewer construction and maintenance work may modify the system's capacities and what influence these facts can have on the pollution of the environment and on urban flooding, only one conclusion can be drawn, i.e. make better use of the existing drainage system by actively directing, storing and treating the flows. The result will be better environmental and flood protection at comparatively lower costs. An example of various approaches to the operation of a UDS can be compared in Figs 2, 3 and 4.

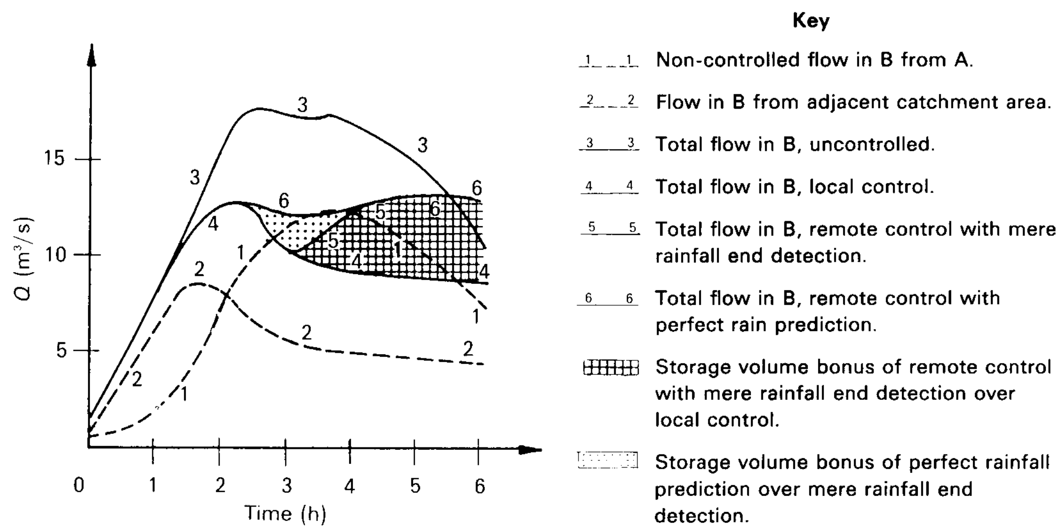


Fig. 3. Hydrographs for location B in Fig. 2 after different modes of control.

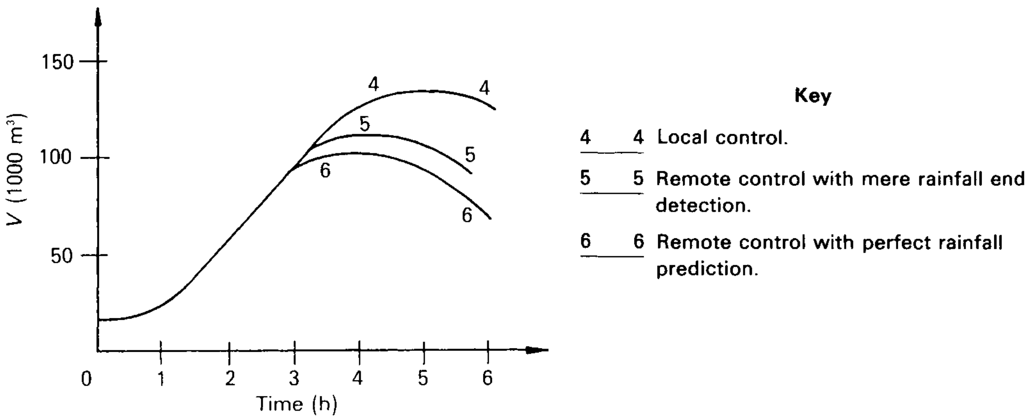


Fig. 4. Stored volume versus time after different modes of control.

2.1.3 IMPACT OF URBAN DRAINAGE MANAGEMENT ON TREATMENT, RECEIVING WATERS AND URBAN ENVIRONMENT

The day-to-day management of UDS is concerned mainly with regular operating conditions such as workers' safety and financial limitations. However, the impact of the UDS on the urban environment cannot be ignored by an UDS manager. Flooding is not acceptable in a society in which it is thought that protection against all types of natural disasters should be provided. Recurrence intervals of up to 10 years for design storms, plus some additional safety factors, result in infrequent large-scale floods. Quite a few localized flood events do still occur due to high local storm intensities, subsequent hydraulic problems and the lack of on-site storage. Temporary sewer blockages due to maintenance work further increase this risk. Urban development increases the runoff volume and the risk of flooding might become worse over the years.

The UDS manager has to comply with standards and regulations on the quantity, and sometimes the quality, of the discharged sewage. Environmental impacts of UDS on the receiving waters are usually not known to the UDS manager, partly because this is not his task, and partly because of the complexity of the problem. Still, he should not be careless about the actual impact on the river. It is well documented that annual discharge loads from combined sewer overflows (CSO) or separate stormwater usually do not constitute the major

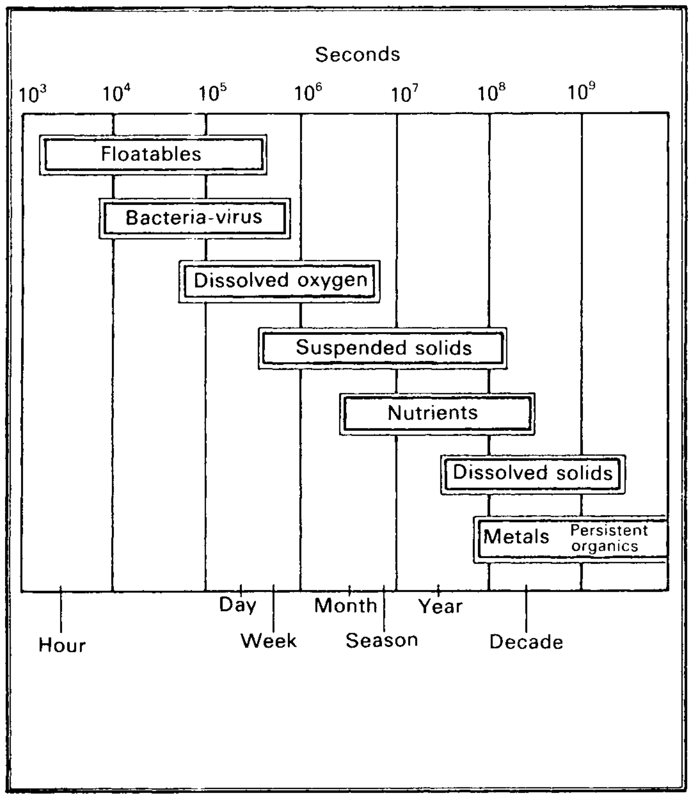


Fig. 5. Time scale of pollutant impacts on receiving waters (adapted from Driscoll, 1976).

fraction of annual pollution discharges. However, since storm discharges only occur during short periods, their impact on receiving waters is not well described by annual loads. It is the intermittent pattern of CSO that mostly impacts on aquatic ecosystems. Features where CSO may produce major disruptions include:

- stagnant or low throughflow in the receiving water (i.e. canals, lakes),
- 'fish traps' (i.e. upstream and downstream CSO into small streams, CSO into dead-end canals),
- low dilution ratio compared to upstream flow, or large urban catchment area compared to upstream catchment,
- low background pollution allowing for a large variety of aquatic life (i.e. little upstream development, efficient dry weather treatment upstream),
- high water temperatures causing low absolute dissolved oxygen concentrations in receiving water (e.g. during summer),
- extended dry periods implying high pollutant concentration from surface washoff and combined and separate sewer sediments,
- high intensity storms producing high flow rates which cause re-suspension of receiving water sediments by hydraulic scour.

Fig. 5 (Driscoll, 1976) gives an approximate overview on the time scale of activity of some pollutants. The relative augmentation of adverse impact of combined sewer overflows on receiving water after improving dry weather treatment is shown in Fig. 6 (Beck, 1981).

Transient flows into treatment plants can cause disruption of the treatment process. Hydraulic shock loads might cause high turbulence in the final clarifier with the result that, in the extreme case, the activated sludge is lost. Pollutant shocks might disrupt the balance of different bacteria species in the activated sludge. RTC of UDS has the potential to reduce these transients to a minimum and, hence, indirectly improves waste water treatment.

Facing this situation, the state-of-the-art in urban drainage cannot be viewed as the final solution. However, proper design and operation of sewer systems, together with an appropriate level of treatment, at least allows the removal and concentration of nondegradable pollutants and the elimination of degradable pollutants to an extent that receiving waters can maintain their ecological integrity. RTC can help to run the UDS and the treatment plant as efficiently as possible to minimize the impact on the receiving water.

2.2 Institutional aspects

2.2.1 PUBLIC OPINION, LEGISLATION AND FINANCE

Willingness to perceive that there is indeed a UDS problem and that money has to be spent to solve it is created through regulatory requirements or public concern, both with environmental quality or flooding problems. Whereas action through regulations seems to be a slow process, public opinion can create significant pressure on the management of a UDS. The increasing pollution of the environment caused a new environmental consciousness in many industrialized countries to support activities in favour of better environmental protection. Public opinion creates a background in which legislators are encouraged to pass laws in *compliance with*

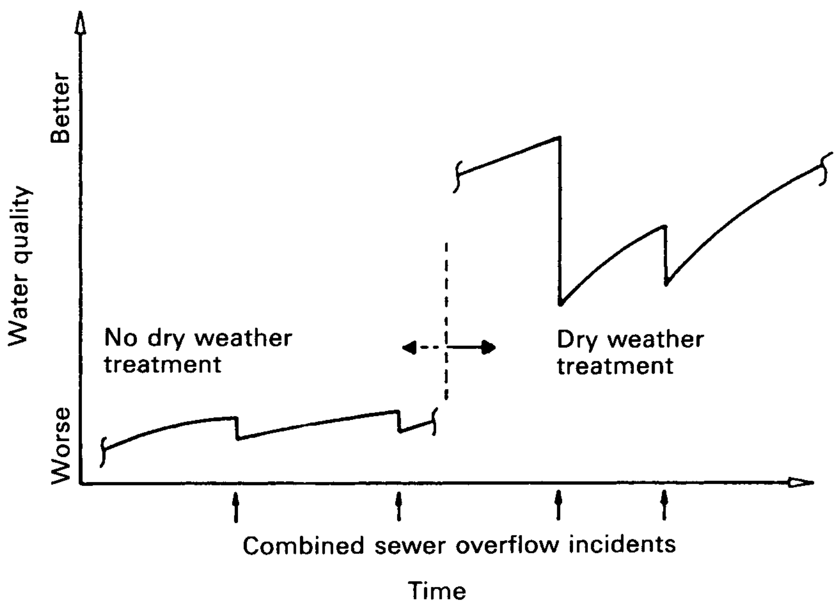


Fig. 6. Relative augmentation impacts of combined sewer overflows on receiving water after improving dry weather treatment (adapted from Beck, 1981).

the state of technology. However, the legislator is not yet aware of what RTC can do for environmental protection.

After problem perception and funding decision, RTC often turns out to be very cost-efficient. In-line storage activated in existing trunk sewers by motorized regulators is usually much cheaper than any large-scale construction for additional off-line storage, tunnels, etc. However, the new RTC system needs to be carefully maintained. Maintenance costs therefore increase because a different kind of maintenance staff, with capabilities in hydraulics, mechanical engineering and electronics, is required. As public agencies finance their investments up to 95% out of state grants, but have to operate their UDS without any outside funds, it is obvious that a low investment, high maintenance, approach such as RTC is not really what a UDS manager wants. For such a funding arrangement, separation of combined sewer systems into separate ones, although more expensive in gross expenditure might be a much more interesting alternative for the UDS manager. These are obviously facts that go beyond any sound engineering reasoning.

2.2.2 STANDARDS AND REGULATIONS

Technical standards and regulations are applied in numerous countries in consequence of the effect of the urbanization process on the urban environment and receiving waters.

Hygienists pledge to enforce separate sewer systems or sewer separation, respectively, as the best way to avoid direct wastewater discharges to the receiving water. In some countries the combined sewer systems are retained but massive additional storage is constructed to reduce combined sewer overflows or flooding problems.

It is only recently that scientists have become aware of the need to bring the regulations to the point where knowledge of environmental impacts and remote information retrieval and remote action are used. Storms with extreme spatial variability are still handled by static flow regulation devices, which have been designed with uniformly distributed rainfall. These design standards are now being challenged by the scientific community. A UDS manager is still protected by law if the sewer is designed for a storm that never occurs (i.e. the design storm) but sometimes he is not if he includes regulating devices that allow the system to adapt for the variability of the actually occurring storm. It is obvious that such a regulation strongly hinders the implementation of RTC.

Technical standards do not prescribe actions that are not feasible. Sometimes, however, the feasible actions do not reflect the intentions and real needs. For example, non-point sources are usually not regulated, but wastewater treatment plants are. So any UDS manager will try to comply with the regulation regardless of what the effect is with respect to the receiving water. Technical standards and regulations help the practising engineer to solve his most pressing problems. However, sometimes they appear as major brakes against improvements which might be reached through consequent use of other more advanced and more site specific technology such as RTC.

2.2.3 SANITARY DISTRICTS AND PUBLIC WORKS

The tasks of operating agencies often end at the legal boundaries of cities or at physical boundaries such as the point of discharge to a receiving water. Design, financing and operation also end at these borders. Sometimes, however, UDS problems can only be solved by looking over these borders.

Administrative agreements between communities create areas within the same UDS which are run separately in order to minimize the complexity of the daily operation. Following the implementation of centralized wastewater treatment and/or sewer separation laws, many large urban areas created sanitary districts which have charge of (small) interceptors and treatment plants, leaving the (large) trunk and collector sewers the responsibility of the works department of each city within the urban area. The operational objectives are separate in that the sanitary district is responsible for water pollution control and the works department for drainage. Whereas this arrangement is useful for static operation it is a major problem for the implementation of RTC. The only large capacity sewers which might be used for in-line storage of wastewater during storm conditions are the trunks which are in the charge of each city. The cities, however, have to guarantee drainage, not pollution control. A city UDS manager would therefore be very reluctant to have 'his' trunk sewers used for decreasing sewer overflows (which is not his task).

Sometimes flood districts are created which are responsible for rivers within the city limits (e.g. Denver/Colorado), or county sewer departments to take care of inter-city sanitary or storm sewers (e.g. Seine-Saint-Denis, France or Ruhrverband, West Germany). The interrelations between cities, counties and districts are relatively clear when decisions are to be taken by the elected board on problems such as construction, financing, etc., but there is a jealous care in daily operation not to be dependent on others. Therefore, it is usually very difficult to implement overall control of the UDS.

2.2.4 DESIGN AND OPERATION

Consultants and other private companies usually play no role in the routine operation of UDS. However, for the planning, design, and implementation phases, consulting engineers dominate, especially in North America. In-house development of RTC systems is relatively uncommon. If this specialization of tasks (consultant: design; public agency: operation) is separated too strictly the success of a RTC system can be at stake. The system might be too difficult to maintain or software might be too difficult to understand and modify. After a few months the system might not be functioning and is ultimately abandoned, leaving the UDS manager angry with the consultant and RTC. This can, however, be avoided. Especially in public service it should be possible to have careful but continuous development and to let the staff 'grow with the RTC system' including the planning, design, and implementation phases.

One also has to admit that RTC of UDS is technically and operationally difficult. A multiphase flow of a mixture of water with everything that possibly flows into a sewer is to be controlled. Consequently, any measurement, regulating, and control equipment has to withstand a very hostile environment. In RTC systems the difference between the desirable and the feasible for materials, devices, and designs is particularly large – a fact that often produces major discords between the planning and the operations divisions of a UDS agency.

It is an interesting fact that universities are not often involved in 'real' RTC projects, although numerous articles on RTC are published in engineering science journals. Obviously there is a severe lack of communication between researching and practising engineers. Hopefully, this can at least partly be overcome by this report.

2.3 Availability of human resources

RTC is an innovative technology. In many cases it is also an economical way to solve UDS problems. But neither technical nor economical criteria are sufficient for successful application. Above all, it is necessary to have a dedicated and enthusiastic core group of engineers, usually small in number, but eager to communicate with the public, the regulatory agency, the executives, and the operating personnel. They are from different divisions such as planning, design, and operations, and are willing to 'look over the borders' of UDS towards treatment and receiving water quality.

Furthermore, the operation and maintenance crews should also have an appropriate knowledge of the behaviour of their system. Attention should be paid to this before actually designing and implementing the RTC system. The operating and maintenance crews must be able to understand features such as basic hydraulic processes or rain gauge records and they must have an idea of the impacts of flows and overflows on the treatment plants and the receiving waters. Operating personnel need strong motivation and backing. Otherwise the risk of making an operational mistake will keep them from using the keyboard at all, or will make them switch back from automatic to manual local control.

If these conditions are fulfilled the RTC system will work satisfactorily. The crew's experience will, after a while, create new ideas for further system improvements and the RTC system will not become an alien element.

2.4. Summary, discussion and conclusions

The historical solution of the problems in designing, constructing, operating and managing UDS is challenged by RTC. The limited efficiency in reducing flooding, environmental pollution and health hazards is caused by the lack of flexibility in the operation of the static UDS under dynamic loading.

The new concept of RTC is emerging to improve UDS performance and to reduce these hazards. A UDS (combined or separate) is operated in real time if process data currently monitored in the system is used to operate flow regulators during the actual process. The objective of this active operation of the UDS is to stop flooding of the catchment and to prevent overflows to receiving waters before the capacity of existing storage is used up. At the same time optimum flow rates to the treatment plant, depending on its capacity and operational state, are to be maintained.

By this means, each particular storm and transient pollution load can be controlled using improved regulator devices and remote monitoring and control systems. RTC is essential for the full use of transport and storage capacities under all operational conditions. Without RTC a UDS can only work optimally for one loading, namely the design storm.

Numerous obstacles to the use of this promising technique might hinder or even prevent the implementation of RTC, e.g.

- administrative boundaries within a physical UDS that constrain possible action within these political limits,
- separation of tasks (pollution control, drainage) in the operation of combined sewer systems which are in fact two-purpose systems,
- funding arrangements that strongly favour high investment/ low maintenance solutions,
- inflexible UDS regulations and standards that prescribe static solutions,
- the belief that RTC should solve all UDS problems immediately,
- the lack of a motivated management and engineering team,
- the lack of skilled maintenance and operation crews.

3. Real-time control concepts for urban drainage systems

3.1 Introduction to real-time control

A UDS is operated in real time if process data, which is currently monitored in the system, is used to operate flow regulators during the actual process. The term 'process' is used here in a strict meaning: the part of the system that lies between input and output variables and where mass transfer is controlled. RTC assumes continuous monitoring and controlling of the process. Real-time systems can be found in many disciplines and consist of elements such as measuring, signalling, communication, presentation, control, operation.

In a more general way the control of a process can be schematized as presented in Fig. 7. In a real-time control system (RTCS) at least one of each of the following elements applies:

- a (measurement) sensor that is used to monitor the ongoing process; e.g. water level gauge,
- a (corrective) regulator that manipulates the process; e.g. sluice gate,
- a controller that causes the regulator to bring the process back to its desired value (set point); e.g. a PID controller,
- a communication system that carries the measured data from the sensor to the controller and the signals of the controller back to the regulator; e.g. telemetry system.

These four elements form a control loop which is common to every RTCS (Fig. 7). The control loop is influenced by external factors such as disturbances (perturbations) of the process and the adjustment (manual or automatic) of the desired control value. The control loop and the way external influences are dealt with, are described in Chapter 5.

For the operation of interrelated variables (e.g. multiple detention tanks or interconnected pumping systems) the notion of global control becomes important. RTC can then be applied to determine the state of the entire system. Optimum performance might be reached if global control decisions are made to achieve a maximum benefit of a pre-specified performance criterion. This can be done by either human beings adapting the process manually or by automatic control which means that operational decisions are made by machines (computers) rather than humans.

3.2 Levels of information and control

It is good engineering practice that the design of a certain operable regulator in a UDS (e.g. a pump) should be such that the regulator can operate completely independently, only on the basis of local variables and criteria. The control and operation of a regulator should in principle be allowed to be independent of the control and operation of the whole unit and the whole system. However, this can be overruled in special situations (e.g. a storm requires a modification of the standard local operation). Then global control will take place from higher levels of control demanding specific actions at the local level. The above-mentioned idea of a hierarchic control structure has been

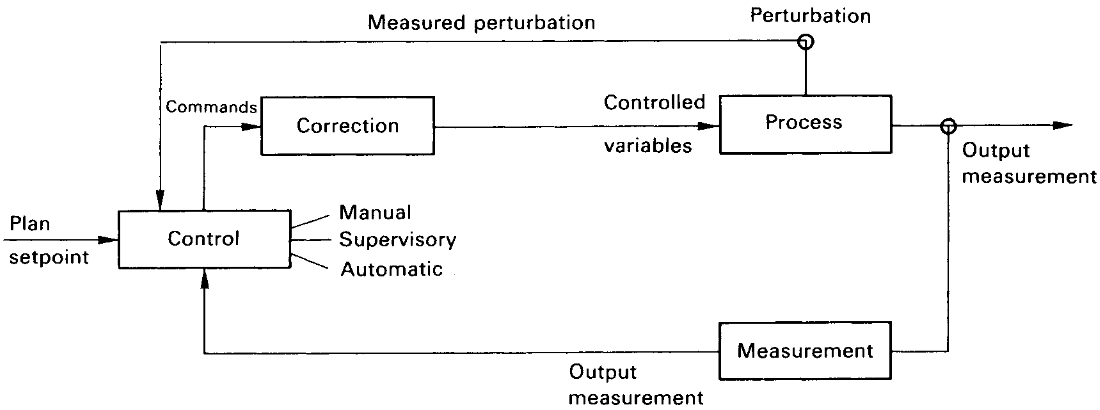


Fig. 7. Schematization of a controlled process (PBNA, 1988).

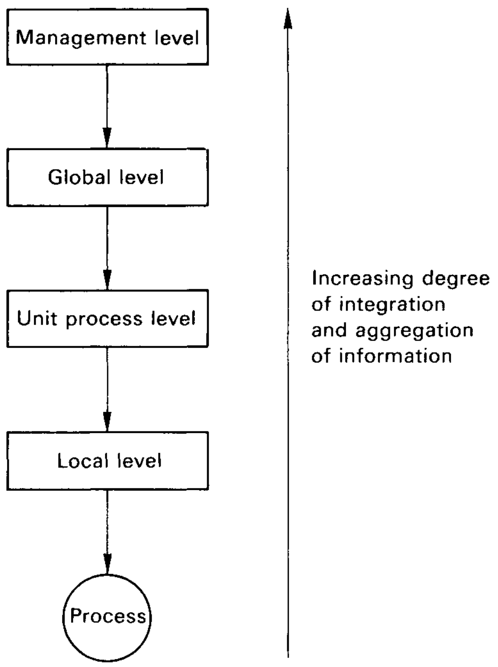


Fig. 8. Levels of information and control.

developed for many industrial applications. It is also useful to apply it to RTC in UDS. Independent operation of regulators in UDS, uniformity and modularity in design are other aspects that also lead to the introduction of levels of control. In general, the following levels can be distinguished (Fig. 8):

- local level (direct level),
- unit process level (regional level),
- global level (overall level, system level, integrated level, strategic level, central level, supervisory level),
- management level.

Because of the fact that, for any kind of control, information is necessary, these levels also represent levels of information. It is evident that, when reaching the management level, the information has to be more integrated and aggregated. Local operation of a pump, for instance, requires other information than determination of the amount of storage to be used during a storm.

In Fig. 9 an example is given for the distinction between a local, unit process and global level. In practice it is neither always possible

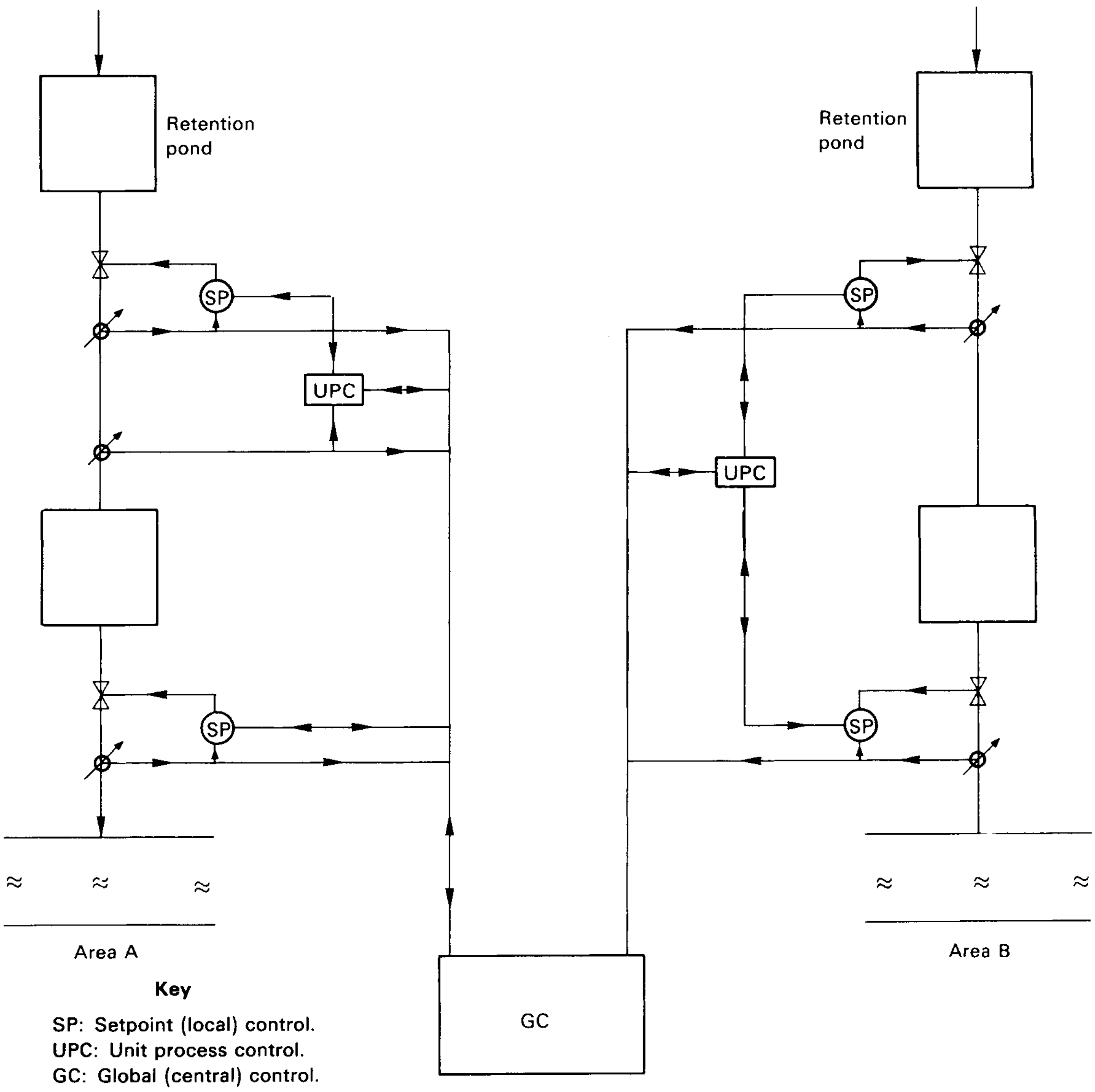


Fig. 9. Example of levels of control (PBNA, 1988).

nor necessary to make a clear distinction between local, unit process or global level. Also the fact that RTCS generally have both geographically decentralized and centralized elements of control and information, is confusing. Nevertheless, it is important to distinguish a hierarchy in control, operation and supply of information in RTC of UDS.

3.2.1 LOCAL CONTROL LEVEL

Operating a UDS means changing the energy component of the controlled variable (e.g. flow) by manipulating regulators such as sluice gates or pumps. In an uncontrolled system an optimum performance level can only be achieved in rare cases, namely if the system is receiving its design load.

Regulators are implemented in UDS to maintain a certain pre-set value (set point) of the process variable. Common to local control systems is that the measurement of the process variable is taken at the regulator site. Other aspects of local control are:

- local manual operation of regulators should be possible,
- elementary safety for maintenance personnel should be ensured,
- signalling of interference or operation is to be transmitted,
- communication with higher levels of control should be available.

Local control in UDS generally also means decentralized control. When there is great uniformity in the controllers of a UDS, it is also possible to make use of one digital computer serving as a controller for all control loops. This principle is called direct digital control (DDC) and is a form of centralization of local control. A DDC system requires wiring between all the sensors to the computer and back to all regulators. DDC relies heavily on the availability and reliability of the central intelligence.

3.2.2 UNIT PROCESS CONTROL LEVEL

Local control as the only control level is a good solution if the system has only one regulator and one decision variable (regulator position). Usually, however, several regulators, either controlled or uncontrolled, do exist and several decisions are to be made (max. allowable storage height, gate opening, etc.).

In those cases, better operation is possible if the set point flows or water levels are interrelated and modified in an appropriate way and at the right time. This has to be done in view of process measurements other than at the regulator site (Fig. 8). This level of control is called unit process control or regional control. Another example of unit process control is shown in Fig. 10 where the unit process level deals with the automatic operation of the complete sewage pumping station (several gate openings, several controlled outputs).

Unit process control is the intermediate level between local and global (central) control: it applies to a part of the system whose output can be defined and is not interrelated with other processes by anything else than its controlled input or controlled output.

In comparison with the global control level there is only relatively little data processing necessary. In some cases the unit process control system has a small mimic panel for manual adjustment of the control system or for emergency operation. Other aspects of the unit process control level are:

- independent operation in relation to other unit process control systems,
- communication with local and central level,
- communication with alarm systems, and
- autonomous safeties within the unit process control.

In general, unit process control systems are decentralized systems. RTC featuring a unit

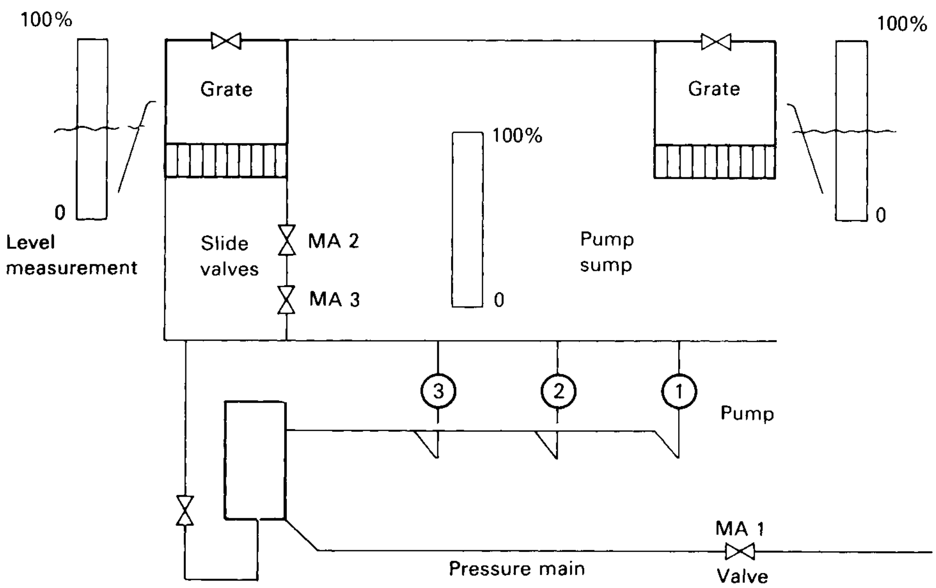


Fig. 10. Unit process control of a pumping station.

process control level can be very simple, only requiring that local control loops should be augmented with remote additional sensors or interconnected between each other, e.g. if long flow time between the regulator and the sensor applies.

Sometimes a unit process control system requires a small telemetry system to provide for the information when interconnecting control loops. An example is a cascade system where the output of the downstream controller is taken as a set point for the upstream controller. A more elaborate form of the unit process control level can be the local control panel of a large sewage pumping station.

3.2.3 GLOBAL CONTROL LEVEL

If a RTCS is more complex (requiring information on the general environment of the system) global control has to be applied. Here, set points and control commands are specified in accordance with process measurements throughout the system. The time sequence of all set point adjustments and control commands is called control strategy. Global control in UDS can be required if one of the following occurs:

- several unit processes exist that affect each other,
- loading patterns are temporally or spatially variable and advantage can be taken of these phenomena,
- strict performance criteria are to be kept,
- management information and operation/maintenance of the UDS has to be improved.

Only with global control can one react flexibly to the rainfall runoff process in every operational situation. However, it is important that the original design criteria of the UDS are still met when global control is applied.

Operational optimization of the UDS may lead to the reduction of the construction cost of the UDS or the treatment plant. That will only be accepted by the authorities when it can be proven that with the application of the global control functions no violation of the design criteria will occur.

Global control systems are generally designed as centralized systems obtaining the process data from decentralized control units by means of a communication network. A central network control system can have several functions which are directly related to each other:

- data acquisition and monitoring of the process, (also alarming is a part of this function, based on the presentation of the most recent state of the RTCS),
- data/information processing based on incoming and outgoing data (elements of data processing include recording, storage, report generation, trending),
- operation and control based on recent, actual and forecasted process data.

Central control of the RTCS can be executed manually or automatically (Fig. 11). Global control may imply remote set point adjustment of local regulators, remote switching of pumps or closing/opening valves or gates. In that way the operational flexibility is substantially enhanced.

3.2.3.1 Manual control

In manual control systems the regulators are operated manually and since only limited information is available, operators need a full understanding or 'feeling' of the hydraulic dynamics of both the control and the drainage system. Manual control is necessary:

- when there is no or only very limited automatic control of the local regulators, e.g. central manual control for pump on/off,
- in the case of maintenance, or
- in case of emergency operation.

3.2.3.2 Supervisory control

In a supervisory control system regulators are actuated by automatic controllers but their set points are specified by the operators. Supervisory control might be switched to manual control in cases of emergency operation or maintenance. Supervisory systems in general provide complete and advanced data processing facilities and are often applied to support the management and maintenance decisions.

Supervisory systems are often a first step into fully automatic global control of the UDS. As with manual control, supervisory control requires experience and feeling for the process dynamics. It can be interactively supported by a simulation system that allows the control effects to be modelled before they are executed. Also, an expert system can be used which contains a data bank of previous control decisions and monitored control effects.

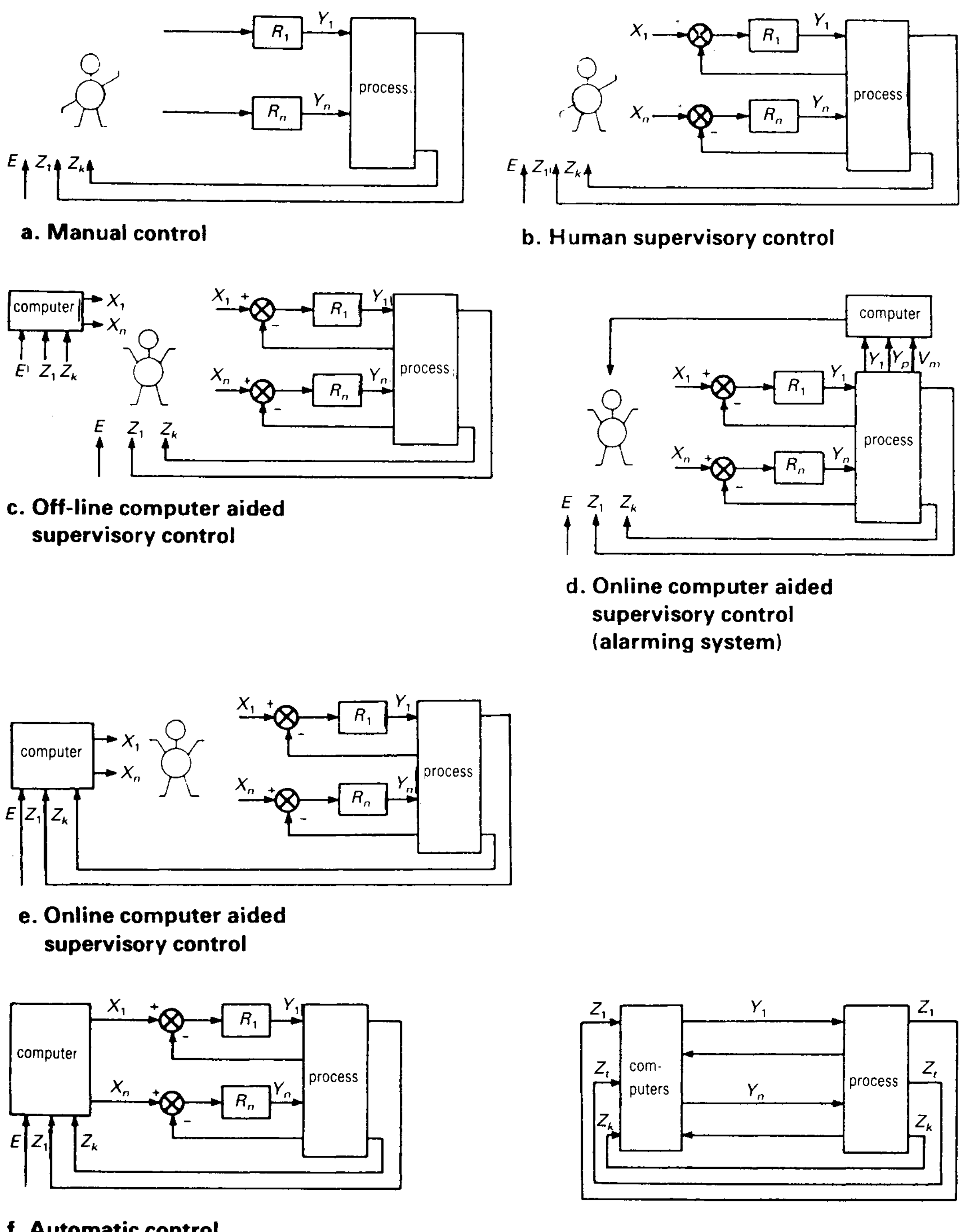
3.2.3.3 Automatic control

In an automatic control system the control strategy is executed fully automatically by a computer. For routine operation, no operator intervention is required. However, the system should be able to allow for manual operation of the UDS in cases of emergency, regulator maintenance, etc.

The automatic control system should provide updated information on the performance of the control strategy as well as tools to adjust the parameters of that strategy. In Chapter 6 several methods to develop control strategies are described.

The state of the art of automatic RTCS design is a combination of decentralized and centralized systems. In such a distributed control concept the decentralized system functions automatically in controlling the regulators and in transmitting information to the central level. At the central level set points are automatically determined for local operation on the basis of the control strategy and transmitted to the decentralized control stations.

With the recent development in networking and communication systems (e.g. local and



a. Manual control

b. Human supervisory control

c. Off-line computer aided supervisory control

d. Online computer aided supervisory control (alarming system)

e. Online computer aided supervisory control

f. Automatic control

g. Direct digital control

Fig. 11. Several forms of global control (PBNA, 1988).

wide area networks) it can be foreseen that fully decentralized global control systems will become available. There, local controllers at the regulator site will communicate with each other through the data transmission network to determine the optimal control policy. In such a decentralized integrated control system the central computer could ultimately become obsolete.

3.2.4 MANAGEMENT LEVEL

At the central control level a large amount of data is collected on the performance of the UDS. These data can be used for the general management of the sewage systems.

Management tasks related to this matter are:

- further data analysis and performance statistics,
- maintenance planning of all the UDS elements such as regulators,sensors, etc.,
- materials and supplies management,
- administration,
- communication with the central level.

For further data processing at the management level, generally microcomputers are applied, connected to the central computer of the real time global control level.

With spreadsheet and database applications on the microcomputer, the data, obtained by the real-time acquisition system, can be processed for management information. Furthermore, at the management level, the global performance of the RTCS may be considered. The objectives of the global strategy may be reviewed (e.g. whether the storage of the UDS is optimally used in relation to the number of overflows, whether the objectives of surface water pollution control are met, etc.).

3.3 Basic design concepts of real-time control systems

The objectives of RTC in UDS are optimum use of storage capacity, minimizing UDS overflows, and alleviating the flow impact to the treatment plant. These can be realized by an appropriate control strategy (Chapter 6). This strategy has to be executed by the hardware elements of the RTCS (Chapter 7). With respect to hardware configurations some basic design concepts of RTCS can be distinguished.

In a RTCS the flow process is continuously controlled through measurements and regulation (Fig. 7). This can be done by means of local (fixed set point) control on the basis of, say, flow or level measurements. Another example of local control is two-point level control of a pump. A low-level limit switch indicates pump start and a high-level switch pump stop.

The same control mechanisms can be implemented in a central computer system for global control of the UDS. Without automatic local control, all measurements and status data of the UDS process have to be transmitted to the control centre. There, the control loops are executed dealing with all the measurements and signals, determining the optimum state of the UDS and transmitting corrective actions by means of commands back to the regulators (direct digital control, DDC).

The concept used nowadays is the combination of both extremes. The regulators are under automatic unit process and/or local control. The status of the process is transmitted to the central control unit. After determination of the optimum state of the process, either set point adjustments are transmitted to the local controllers or commands are transmitted that directly influence the status of the regulators.

The levels of control have been introduced in the preceding chapter. It is also important to consider the effects of manual operation on the automatic control of UDS. Several levels of influence can be distinguished (Fig. 12):

- manual local operation always has to overrule other control commands, i.e. maintenance staff must not be exposed to control actions due to remote commands during on-site maintenance of a regulator,
- remote manual operation or supervisory operation always has to overrule automatic control of the regulator,
- central (global) automatic control determines the local automatic operation unless independently working local alarms prevent this,
- when there is no communication between central and local level, a watchdog system determines local automatic operation.

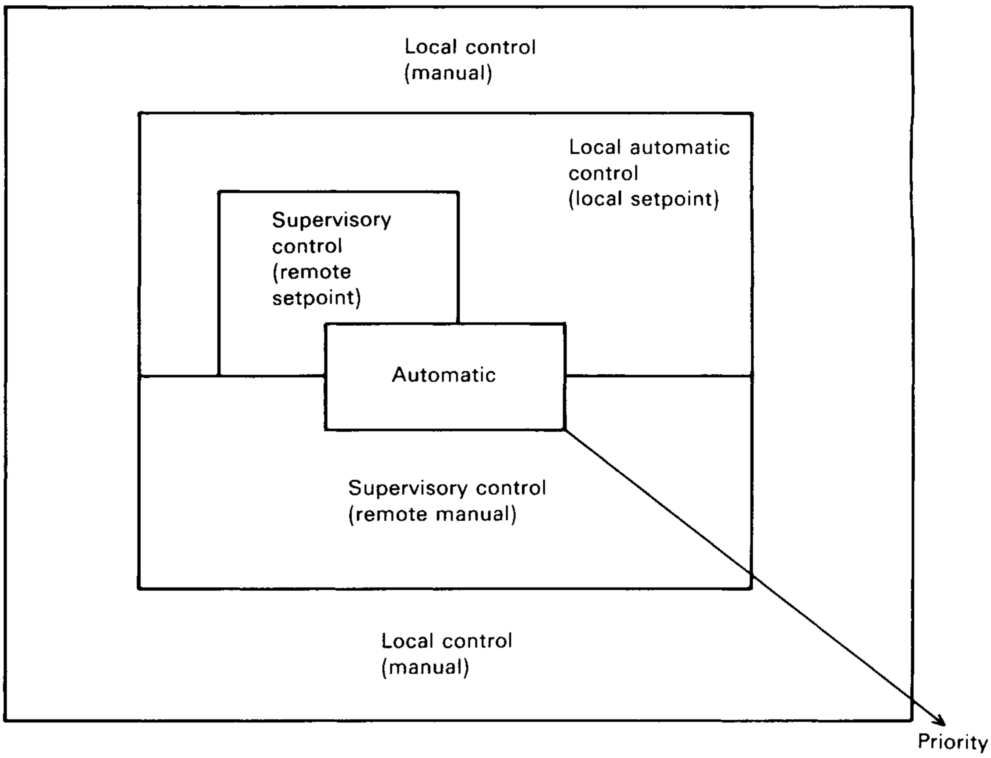


Fig. 12. Priority levels in an automatic global control system.

Furthermore, it depends on the requirements of the specific UDS whether manual operation (remote or local) should also influence other parts of the UDS, possibly actuated through the RTCS. Taking a pump out of operation for maintenance purposes, for instance, may require that other pumps also should be stopped. This can be done automatically as a part of the strategy or as part of a maintenance scenario carried out manually.

A RTCS requires a number of elements which are especially developed for (real-time) control purposes. These elements consist of hardware such as regulators, measurement devices, etc., and of data that has to be transmitted and processed to determine the control strategy. These elements are discussed briefly below and Chapter 7 deals with the hardware aspects in more detail.

3.3.1 HARDWARE REQUIREMENTS

The basic control loop, as shown in Fig. 7, needs several devices to carry out the necessary functions of control. The process parameters and the changes in the process due to external influences have to be detected by measurement devices.

The measured signals have to be transmitted to the controlling unit by means of a directly wired link or by a telemetry communication network. The controller, when situated at the regulator site, may also be a part of the communication network. Finally, the output signals of the controller have to be transformed and transmitted to the regulator to correct the process variables.

3.3.1.1 Sensors

The most common parameters measured in RTC of UDS are wastewater flow and level. Quality parameters are not very often monitored due to the limited reliability and the high cost of the sensors. In Chapter 7.1 the aspects of the application of sensors in RTC of UDS are discussed in more detail.

The measured signal might be analog, represented by a certain voltage (0–5V) or current (0–20 mA or 4–20 mA) and has to be transmitted to the controller and/or the central supervisory system. The controller that receives the signal, has to cope with hysteresis, signal disturbance, electromagnetic interference of the sensor, etc.

Sometimes, the analog signals are transformed into digital signals (e.g. 0–255, 8 bits). Sensors are regularly scanned by the data acquisition system, using a scanning cycle in the order of seconds to minutes.

3.3.1.2 Regulators

As already stated in Chapter 3.2, local control implies regulator action, independent of other elements of the UDS. Additionally, the regulator might be influenced from a higher level in two ways:

- the set point might be adjusted at a higher level (e.g. central adjustment of a set flow through a regulating valve),
- high level commands might shut off the local automatic operation of a regulator which is usually carried out by relays. For example, a pump under local automatic operation during dry weather might be taken under global control during heavy rainfall.

The latter system can also be used for the implementation of a watchdog system that puts the regulator into sub-optimum but safe, predetermined local operation when global control is out of order.

Usually it is attempted to keep local controlling devices as simple as possible to minimize investment and maintenance cost. Examples are, among others, vortex valves, float regulated gates and air regulated syphons. However, these regulators do not allow for changing set points during the process, i.e. they only allow for local control but not for unit process or global control.

Other relevant aspects of basic design concepts in the control of regulators concern the level of information and operation, such as:

- local operation (manual, auto, off, set point adjustment, speed regulation),
- safety systems,
- signalling of the state of the regulator,
- measurement and local display of controlled parameters,
- communication with higher levels, such as external command relay, signalling of manual operation, external set point modification.

It depends on the desired level of information and the operational hierarchy in the specific project, whether the above-mentioned elements should be applied.

3.3.1.3 Input/output devices

Controller functions are very well suited to be carried out by microprocessors which are programmed for the execution of the process control logic. To connect the signals from the field (regulator, sensor) to this controller and to prepare output signals from the controller to the field equipment, input/output (I/O) devices are used (e.g. I/O-boards in the I/O connection units). Analog input signals have to be converted into digital code and digital output back into an analog signal when using digital controllers or digital communication systems. The I/O-devices for digital systems are described in more detail in Chapter 7.4. In RTC systems I/O-devices are often located in remote telemetry stations and sometimes in central computer systems.

3.3.1.4 Telemetry

Only where sensor and regulator are very close to each other can the input/output of the data be analog, e.g. pneumatic, hydraulic or electric current. When distances between the sensor and the controller or between the sensor and the central data processing system are too great, communication is generally realized through a digital telemetry system.

A telemetry system consists of one or several telemetry stations located at the sites of regulators and sensors or a group of such devices. The telemetry stations communicate with a central unit or with each other. The communication network is usually a telephone network in which either leased or dialled lines can be used (Chapter 7.3). The central system consists of a telephone exchange unit and a subsequent computer system for further data processing and execution of the global control strategy.

The RTCS should be designed in such a way that all kinds of interferences can be detected and dealt with in the telemetry network such as:

- malfunctioning of a telemetry station,
- electromagnetic interference of the communication system,
- break down of the central unit.

Essential or vulnerable parts of the telemetry network should therefore be designed redundantly.

3.3.2 INFORMATION PROCESSING

RTC of UDS requires a large amount of data to be processed and information to be provided, especially in a centralized global control system. Information processing is required for:

- the execution of the control strategy,
- the monitoring of the RTCS as well as system supervision,
- the maintenance of the UDS and the required operational actions,
- alarms,
- emergency control of the UDS,
- the management of the UDS.

These elements of central supervision and management of the UDS require different kinds of information. Therefore the data has to be acquired and processed afterwards as well as stored and presented. This includes:

- documentation of all incoming status signals on printer,
- detection of incoming alarm signals,
- emergency signals for the operator,
- presenting most recent status data of the RTCS on a mimic panel or a graphic (color) display,
- storing data for protocol reports,
- report generation on a printer,
- storing measured values for trending analysis with graphic display and using plotter presentation facilities,
- presentation of recent process data and set points on display to execute command control actions or manual set point adjustments,
- logging and storage of manual control actions to the UDS,
- storing recent data for the automatic execution of a global control strategy.

In older control systems, measurements and signals are presented on meters, lamps, light emission diodes (LED) etc. which are located in the control room. Nowadays, due to the developments in computer technology, advanced supervisory control systems are available. They feature screen displays, color graphics, windowing software and user friendly input devices such as a mouse. These systems are provided with standard software for supervisory and monitoring functions. However, global control aspects usually have to be developed for each application. Fig. 63 is an example of the organization of the software of a central information processing and control system.

3.4 Summary, discussion and conclusions

Real-time control assumes continuous monitoring and controlling of the flow process. In principle, the control of a process can be schematized to a simple control loop. This control loop requires a sensor to measure the process, a regulator to adjust the process and a controller to activate the regulator. Between these elements data have to be transmitted.

In RTC of UDS several hierarchic levels of control can be distinguished, i.e. local control, unit process control, global control and central management, with the latter being the top level. Depending on the requirements of a specific UDS, the control can be completely decentralized, fully centralized, or some mixed arrangement such as decentralized local control with central global control.

Distributed systems are most common in practice. They allow for local automatic control of the regulators and for central modification of the local control. Communication in a distributed system is usually realized by a telemetry network using public telephone lines. Global control can be executed manually (supervisory mode) or automatically (central automatic mode). It should allow for dealing with all kinds of interference, be it malfunctioning hardware, communication system failure or on-site manual operation.

In a global control system a large amount of data has to be processed to supervise the day-to-day performance of the UDS as well as to check the effects of the applied control strategy.

4. Modelling the state of an urban drainage system

4.1 Information requirements

A UDS does not have a constant output. Its tasks and operating conditions change with the risks involved: flooding, pollution construction work, safety, etc. Therefore a RTCS design should start with a thorough selection and quantification of the decision variables which are output of the system, and of those which are controlled.

4.1.1 DECISION VARIABLES

Examples of desired output variables are:
- construction site throughflow below sump pump capacities whenever the risks of storms are low,
- removal of a construction site protection barrier whenever the risk of a storm is high,
- no overflows to the river when the risk of a storm is low,
- basement or street flooding volume to be minimized during heavy storms,
- regulated variables as close as possible to the predetermined set point values.

Controlled variables include:
- flow at a storage outlet,
- intercepted flow to the treatment plant,
- authorization of use of a storage basin.

The selection of the output variables is not an easy problem. It requires:
- understanding of the transient process occurring within (e.g. stormflows) or at the borders of the drainage system (treatment plant),
- a hierarchy within the selected set of variables, which can be modified according to known or forecasted transients.

Controlled variables are usually flow dependent and a knowledge of the control range for them is needed.

4.1.2 RESPONSE AND REACTION TIMES

The main feature of RTC is the importance of time: action should be taken soon enough so that the effect of regulated variables on output variables occurs before output variables exceed their allowable limits. In Fig. 7 a generalized scheme of RTC is given. One should note:
- the system response time, which is the time lag between a disturbance of a controlled variable and the time of the subsequent output variable response,
- the reaction time, which is the time needed to process information either on measured output or on measured disturbances, until the controlled variables are properly adjusted.

In a computer aided supervisory mode the reaction time includes (Fig. 11):
- scanning time of input signals,
- data acquisition time,
- computer data processing,
- human decision time,
- transmission of output signals (set points, commands),
- controller data processing,
- regulator speed.

Therefore, one should keep in mind that some data such as measurements of output variables could be of no use if the system response time is longer that the system reaction time. Also, should control loops be hierarchically organized and information be selected at each control level (local, unit process and global)? Decision variables have to be properly selected at each control level so that system response time never exceeds the reaction time.

4.1.3 USE OF MODELS

The selection of decision variables requires a thorough knowledge of the actual process and its response times. The only way to acquire this knowledge is through the use of models for simulation at each control level:
- transfer function models of the regulators can be used to evaluate parameters of controllers such as PID (proportional, integral, differential) controllers,
- hydraulic transport models are used to simulate unit processes such as a single retention basin or a cascade of two basins,
- with global models disturbances are estimated and forecasted and their effect on the system is modelled: these might be surface runoff pollution, dry-weather pollution, etc. The global model is also used to simulate the controlled system (e.g. downstream of the regulators, flooded areas). Finally it might be also designed to simulate the output effect on treatment plant and receiving waters.

In principle, all of these models can be used on-line as part of the control system, but more frequently they are used off-line in the RTCS planning and design stages.

4.2. Modelling of system disturbances

4.2.1 AREAL RAINFALL

This chapter refers primarily to papers by Andrieu (1986), Einfalt and Denoeux (1987) and Denoeux *et al.* (1987). The measurement of runoff at the entry points of the hydraulically controlled network may often prove that the reaction time is greater than response time. In other words, flow time is too short to react properly. In these cases areal rainfall models for subcatchments of which the outlet is an entry point to the controlled network are useful tools. This estimation can be done:

- from point rainfall measurements,
- from indirect surface rainfall measurements such as radar reflectivity measurements coupled with rain gauges, or
- from forecasted movement of rain cells using a sequence of radar images.

Models derived from point rainfall measurements are always interpolation models such as the simple Thiessen model, linear interpolation, or the 'kriging' approach based on the theory of regionalized variables. Although the latter gives the best average fit for a large number of rain storms, none of these techniques allows the estimation of areal rainfall for single storms as precisely as needed. It is estimated that the rain gauge network density has to be about 1 rain gauge per km^2 for this purpose – a density which is usually considered too expensive.

Areal rainfall models using calibrated radar measurements have proved to be very efficient except for the measurement of very small showers in which high variability of rain intensities occur (Jacquet *et al.*, 1986).

Areal rainfall forecasts of 30 minutes using radar seem to be reliable enough for runoff modelling in a large number of meteorological situations. However, about one third of these forecasts might not be accurate enough unless an associated predictive model based on image analysis and knowledge of atmospheric stability is also used.

4.2.2 RUNOFF

Runoff models are needed in conjunction with areal rainfall models to estimate the flow at entry points of the hydraulically regulated networks. They include models for surface runoff and uncontrolled pipe flows.

Although physically based models are used for, say, roof runoff, surface flow, gutter flow, etc., nowadays mostly black box deterministic models are used for UDS analysis (Jacquet, 1982; Wisner, 1986).

These models feature a loss approach to estimate the effective rainfall and an impulse response function to compute sub-catchment runoff from effective rainfall. As loss models several types of functions might be used such as:

- effective rainfall as constant percentage of gross rainfall, usually taken as the percentage of impervious areas,
- constant percentage after initial losses (from 0.5 to 2 mm),
- time variable percentage of active surfaces (impervious or pervious).

The impulse response function could also be of several types, usually assumed to be time invariant:

- single linear reservoir model,
- cascade of linear reservoirs,
- triangular-shaped unit hydrograph (of which the base time is the calculated longest flow time within the sub-catchment).

Experiments in urban areas have proved the validity of using a time variable loss function (Bertilotti *et al.*, 1986) and a directly estimated triangular unit hydrograph. As far as computational speed is concerned, all models perform approximately equally fast. In any case, computation time is totally negligible compared to the response time of the hydrograph.

4.2.3 SURFACE POLLUTION AND SEWER DEPOSITS

With the rainwater follows a variety of pollutants, some as a result of atmospheric washout, but the most substantial part as a result of washoff of pollutants deposited on surfaces during dry weather periods. Roads and other paved areas contribute large quantities of solids, organic pollutants, heavy metals and hydrocarbons (Olie *et al.*, 1982).

From the atmosphere airborne pollutants are washed out. When the raindrops reach the ground their impact may loosen parts of the surface and pick up particulate matter. As the water flows on the surface, particulate matter will either be transported or deposited (wet deposition), depending on the flow velocity, and soluble matter will be picked up and transported to the inlet of the sewer system.

Type and concentration of pollutants in surface runoff depend mainly on the location of the catchment and of the land use. Furthermore, the concentration depends on rain intensity, rain volume and to some extent on the duration of the antecedent dry period (Deutsch and Hemain, 1984).

As a result, the surface runoff pollutographs (concentration versus time) vary in time and do not necessarily follow the hydrographs (flow versus time). In the context of real time control, this phenomenon provides a way to reduce pollution loads to receiving waters by operating overflow structures so that when overflow occurs it should be the least polluted water that leaves the system. In order to establish the surface runoff pollutograph it is necessary either to measure or to model it. On-line measurements of parameters such as BOD, nitrogen and phosphorus, cannot at present be done both accurately and reliably. Modelling of the surface runoff pollutograph has also not been encouraging.

Surface runoff pollution is considered as being input to a controlled sewer system since the incoming pollutographs can not be controlled in real time. The general level can to some extent be controlled by street cleaning and cleaning of gully-pots, but in real time no control can be performed on surface pollution.

Sediment deposits in the sewers are also a major pollution source. Mechanisms and the potential to control their discharge by RTC will be discussed in the following chapter on pollutant transport. One has to be aware of the importance of these wastewater deposits especially in combined sewers (50% of CSO biodegradable matter, on yearly average, could be due to this source) and even in storm sewers due to incorrect connections.

The simplest way to simulate wastewater pollutant is through correlation analyses which have been made with respect to density of population, surface slopes, etc. Deterministic modelling of the pollutograph would require quantity and quality models for sanitary wastewater, infiltration, surface runoff and sediment transport for relatively small time steps. Models for surface runoff quality and sediment transport are still not accurate enough, though many attempts have been made (Harremoës, 1986).

4.2.4 DRY WEATHER POLLUTION

Models of dry weather pollution are primarily time dependent in that the pollution load can be computed from the knowledge of time and day of the week, month, etc. Careful measurements are always required to take industrial effluents, infiltrated water, hourly, daily, and seasonal variations, etc. into account.

4.3 Modelling of the system state

The term 'system' is not used in this paragraph as the whole UDS, but only the part which can be controlled by regulators. Input to this system can be surface runoff, flow from upstream branches with no RTC possibilities, sanitary sewage flow and infiltration. The controlled drainage system includes transport elements (conduits) and a number of various structures such as manholes, ponds, overflows, pumps and static or dynamic regulators.

Modelling the state of the system for RTC has two purposes:

- in the planning (off-line) phase, modelling is used to design the drainage system and to determine control strategies and to predict system performance,
- in the operational (on-line) phase, modelling can be used to supervise and modify control strategies during the flow process.

Based on measurements (and forecasts) of rain, inflow to the controlled system can be computed. These data, together with the computed and/or measured state of the system, are used to control the system.

The advantage of both on-line and off-line modelling is that the state of the entire system can be determined, although measurements are only available for some points of the system. Information on the entire system is required to determine the optimal control strategy, possibly supported by additional inflow forecasts. For both tasks a certain degree of modelling accuracy is necessary. For on-line purposes, high computing speed is an additional necessity.

4.3.1 HYDRAULIC TRANSPORT

The physics of sewer routing in open channels are described by the Saint Venant differential equations. The numerical solution of these equations and the introduction of the so-called Preissman slot in order to simulate pressurized flow, represent the most accurate tool available, but also the most complicated models to use. The application of these models is usually relatively time consuming.

Neglecting terms of the Saint Venant equations leads to faster models, like the diffusive wave, kinematic wave and simple time shift routing models. However, this is achieved at the cost of a reduced accuracy.

Introducing controllable weirs, gates, etc. in a drainage system might call for the use of the fully dynamic wave models, since phenomena like backwater and pressurized flow are likely to be of importance. If the model is used on-line, it is very important that surcharge and flooding are simulated as accurately as possible, since these are the major control objectives to minimize.

Careful analysis of the actual catchment might lead to compromises both on system description and model complexity, without severe loss of accuracy (Schilling and Fuchs, 1986).

4.3.2 FLOW THROUGH SPECIAL STRUCTURES

Simulation of flow through special structures like ponds, overflows and pumps is generally handled in the existing models. The accuracy is mainly dependent on the level of sophistication of the flow routing part.

Controllable weirs, gates, etc. with the control strategy based on water levels or inflow, measured or modelled, in one or several points of the system, can to some extent be modelled by only a few of the existing models. This is not due to any theoretical problems caused by introducing this feature in the models, although fast moving weirs or gates might lead to instability problems. This is merely due to the fact that until recently there has been no demand to have these features included in UDS simulation models. In the relatively few instances when models have been used for RTC purposes, models have been developed for the specific catchment (Brandstetter *et al.*, 1973; Rennicke and Pollak, 1976).

4.3.3 POLLUTANT TRANSPORT

Pollutant transport is usually dealt within the system as a simple convective model without diffusion. Hardly any of the existing models include solid deposition and resuspension which might be needed in some cases (e.g. low gradient CSS).

One of the main sources of CSO pollution is the sedimentation of particulate matter due to low flow velocity of waste water in dry weather periods. This sediment layer in the pipe system can be resuspended during storm runoff. The result is a higher mass transport of pollutants than the one expected from the mixture of sanitary wastewater and stormwater (Jacquet, 1975). The significance of resuspension of sediments on the pollution loads from sewer overflows varies greatly from one section of a UDS to the other. This is due to different construction concepts that include or neglect self-cleansing effects (Lindholm, 1984). The combined pollutograph, being a result of sanitary wastewater, infiltration, surface runoff and resuspension, has the same features as the surface runoff pollutograph. It is time varying and does not necessarily follow the hydrograph. The occurrence of this flushing effect might result in a potential benefit of RTC if the operation of overflows could be based on the actual pollutograph. At present this does not seem to be possible since reliable on-line measuring equipment for parameters such as BOD, N, P do not exist. On-line sensors for BOD (3 min.), COD, N, P or for other related parameters do exist, but their operation in the sewer system environment does require very frequent calibration. Since they are subject to interference from other water quality parameters, results are rather doubtful.

4.4 Modelling of output effects

From the controlled sewer system, water is conveyed to a treatment plant and, if necessary, directly to receiving waters through overflow devices. The introduction of RTC in a sewer system results in a better utilization of the storage capacity in the system and more water is passed through the treatment plant and less is passed directly to the receiving waters. At the treatment plant, this can result in a decrease of effluent quality, since the hydraulic load will be higher for a longer period. In an activated-sludge system this influences the performance of the final clarifier. If both the overflows and the treatment plant are discharging water to the same recipient, this could mean that no reduction, or worse, an increase of pollution loads (BOD, N, P), is achieved. Models to describe such a phenomenon are obviously needed.

4.4.1 OUTPUT EFFECTS ON TREATMENT PLANTS

Out of the many unit operations in traditional wastewater treatment plants, there are four which have considerable influence on the overall performance:

- primary settling,
- trickling filters,
- activated sludge,
- final clarification.

The effluent quality, with respect to suspended settleable solids from the primary settler, decreases significantly if inflows increase. This, however, hardly influences any biological treatment process after the primary settler.

The controlled sewer system can, in opposition to the uncontrolled sewer system, be operated so that hydraulic shock loads are prevented. Thereby, a washout of the total solids contained in primary settlement can be prevented. This is especially important if primary settlement is the only treatment carried out.

The trickling filter is generally not affected by an increase in hydraulic load, since the design of the distributor limits the flow through the filter. This results in effluent concentrations during storm water treatment similar to those during dry weather conditions.

The activated-sludge process is not very sensitive to high hydraulic loadings. The effluent concentration of soluble organics is only increased slightly, if the aerator capacity is sufficient and if sludge settling and recycling is not disturbed. Even with insufficient aerator capacity the activated-sludge process still reduces the concentration of soluble organics considerably if the duration of hydraulic overloading is not too long.

Secondary settling after trickling filters can never be overloaded because of the hydraulic limitations in the trickling filter. Even if this should happen it would not be a serious threat to the environment, since the concentration of suspended solids is low.

Secondary settling after an activated-sludge process is more of a problem if the hydraulic loading is too high. Activated-sludge plants do not have the same built-in flow limitations as trickling filter systems. Furthermore, the concentration of suspended solids in the settler is very high. The secondary settler is very sensitive to rapidly increasing hydraulic load, which in extreme cases might lead to a total breakdown of the plant performance with effluent concentrations of BOD at the level of 2000–3000 g/m^3.

A controlled sewer system upstream of the treatment plant allows an input hydrograph to be smoother. Thereby, the performance of the secondary settler during storm conditions can be improved. However, since the mean hydraulic load increases in a controlled system, there is a risk that the sludge blanket in the final clarifier rises to the top of the settler and overflows. This problem has to be avoided by proper settler design.

To model the total output of pollutants from a treatment plant during storm conditions requires models for the above-mentioned four unit operations. The primary settler can be modelled by simply establishing a relation, based on measurements, between flow and effluent quality. This has to be done for the actual settler and is also dependent on the wastewater characteristics.

Models of trickling filters have not been developed yet beyond the formulation of the simple reaction kinetics with empirical equations. In this context however, modelling of the trickling filter is not very important, since the effluent quality does not change significantly during storm events due to the inflow limitation set by the distributor.

The basis for a complex mathematical model for the activated-sludge process has been developed by an IAWPRC Task Group on Mathematical Modelling (Henze *et al.*, 1987). The model has been developed for single sludge systems performing carbon oxidation, nitrification and denitrification. This model, which represents the present state-of-the-art, needs a very detailed characterization of the wastewater quality which has to be based on measurements for every single plant. This model could be very useful for off-line planning and design of the controlled sewer system (Jacquet, 1982), provided that proper input data can be simulated by a pollution transport model for the sewer system. Due to the long retention time in the treatment plant it is not so important to model the incoming pollutograph in detail for time steps as short as 1–2 minutes. Average values for 30–60 minutes can be used. These can be simulated by existing pollution transport models if they are carefully calibrated with measured data.

The performance of the secondary settler can, like the primary settler, under normal conditions, be modelled by a simple flow/effluent quality relation, based on measurements. Modelling the rising sludge blanket and the eventual breakdown of the settler, due to high hydraulic loading, is a much more complicated task. Models for this purpose have been developed using the so-called flux theory to describe this phenomenon.

4.4.2 OUTPUT EFFECTS ON RECEIVING WATERS

The effect of wastewater discharges on the receiving waters is a function of the type of the recipient and the nature of the discharged substance. Pollution problems from discharges can be divided into the two categories of wet weather and dry weather discharges.

Acute effects are due to toxic material, oxygen depletion, erosion, and bacterial contamination. Acute effects have to be evaluated on the basis of individual events that may cause the damage (Clamagirand and Gaillard, 1986; Harremoës, 1982).

Accumulated effects can be due to nutrient eutrophication and accumulation of heavy metals in biomass and sediment. In this case it is the accumulated discharge over a characteristic period that has to be evaluated. Accumulated effects can also be due to slow oxygen depletion from sediments (Villeneuve and Lavallee, 1985). Small lakes and rivers are under long-term oxygen depletion due to organic and nutrient sediments.

Other effects of discharges concern aesthetics, beach protection, etc. Effects of this nature are observed by the public. Their social costs are difficult to quantify.

Dry weather (accidental) discharges of untreated wastewater might create problems depending on their toxicity and the downstream use of water. Sudden drops in quality may have an adverse effect on purification for water supply. Therefore, modelling of short-range effects might be useful.

4.5 Discussion and conclusions

In the context of RTC the meaning of 'system' is the controllable part of the UDS. A real-time control system (RTCS) can be planned thoroughly if (numerical) simulation models are used. The following processes have to be modelled in order to obtain a comprehensive overview on the performance of the system:

- the input to the system,
- the systems response to the input,
- the total output to the environment,
- the response of the environment to the output from the system.

Modelling of the input to the system is generally based on rain measurements, a surface runoff model and eventually a pipe routing model including wastewater and infiltration input. The sensitive part of the input modelling is the rain input, where phenomena like spatial distribution of rainfall, and growth, movement and decay of rain cells, play a major role. So far, there do not exist any models that incorporate these phenomena in a deterministic way. However, with a fairly dense network of rain gauges adequate rain input to a surface runoff model can be obtained. Another way of obtaining rain input data is the use of the radar technique which also provides a possibility of rain forecasting and a proper description of the spatial distribution of rainfall. The radar technique is operational in a few European and North American regions. Effort is being put into this field to make it more widely available for RTC in UDS. Pollution input to the system is more difficult to model and further work is necessary to establish a fair basis for modelling of the pollution input to the system. Models for the state of the system, including modelling the input to the system have been developed in a great number for static, non-controllable systems. However, hardly any model has been described for the simulation of automatic regulators and external control input during the simulated process.

Hence, for the purpose of planning, analysing and operating real-time control systems there is a need for further development of models that include simulation of automatic regulators.

Pollution transport in the system is also a subject on which further work is needed in order to develop models which can simulate overflow pollutographs or treatment plant inflow loads. Presently no urban drainage models exist that also include simulation of the treatment plant. However, separate treatment plant models exist which, after coupling with an urban drainage quality model, could be used to simulate outflow from the treatment plant.

The impact of combined sewer system overflows, separate system discharges and effluents from treatment plants on the receiving water quality can be modelled by some of the existing models for some parameters. However, their effects on the organisms living in the receiving waters are much more difficult to predict. Little is known on this subject let alone applied in UDS management and operation.

5. Basic control techniques

5.1 Definitions

FROM the point of view of basic control techniques a UDS can be regarded as a system which is surrounded by an environment. Between the system (UDS) and its environment, certain interaction occurs (rainfall, overflow). This interaction can be described in a control model as the action of:

- input variables (input signals, independent variables: representing the influences of the environment on the system),
- output variables (output signals, dependent variables: representing the influences of the system on its environment).

A control system can be viewed as an artificial system in which one or more process variables behave in a predefined way. A process is the time sequence of those variables that determine the state of the system. This predescribed behaviour of a variable could be:

- stabilizing the output variable of the controlled process,
- subsequent action: the output variable of the system has to follow the input variable within certain limits,
- sequence operation: the output variables act according to a predefined program (sequence control).

Control systems can be divided into two general categories of open control systems and closed control systems.

5.1.1 OPEN AND CLOSED CONTROL SYSTEMS

Open control systems consist of a process and one or more control chains (Fig. 13). Within the control chain the impacts of disturbances on the process are not measured. Open control systems are systems **without** backchaining. An open system has the following characteristics:

- its control performance is determined by calibration of the controller, i.e. the similarity of assumed and actual disturbances of the controlled process,
- open systems do not suffer from instability problems.

An example of an open control system in UDS is the time-sequenced control of pumps. The time a pump is operating is predefined and determined on the basis of experience (calibration). The pump operation periods are determined (input value) but there is no control on the resulting flows and water levels (output variable).

Closed control systems are systems **with** backchaining (feedback). In these systems the variable to be controlled is also measured. If deviations from a pre-specified set point occur the controller activates a regulator to reduce this deviation. Backchaining can be carried out in several ways:

- by intervention of the operator in the closed loop system (manual control),
- by automatic controllers (automatic control).

In Fig. 14 the elements of an automatic closed loop control system are shown. The automatic controller consists of three elements:

- the measuring element,
- the comparator where the set point and the measured values of the controlled process are compared,
- the controller, which outputs the control commands.

Closed loop systems are very often applied in RTC of UDS, e.g. the control of a reservoir level (Fig. 26) or the maximum outflow from a storage pond (Fig. 15).

5.1.2 CONTINUOUS AND DISCRETE CONTROL SYSTEMS

Continuous control systems can be defined as control systems in which signal processing is continuous in time. They can be described with differential equations, which are models of the process of the state of the system.

Discrete or discontinuous control systems are systems in which signals are available or monitored at discrete moments of time. In such a control system information is processed at discrete time intervals. Their behaviour can be described with difference equations. When the information is in a digital form, such a system is called a digital control system.

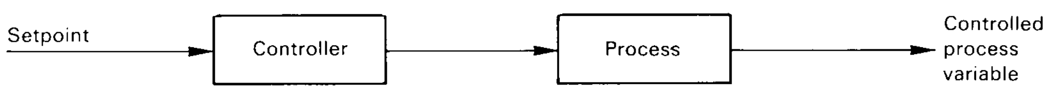


Fig. 13. Open control system.

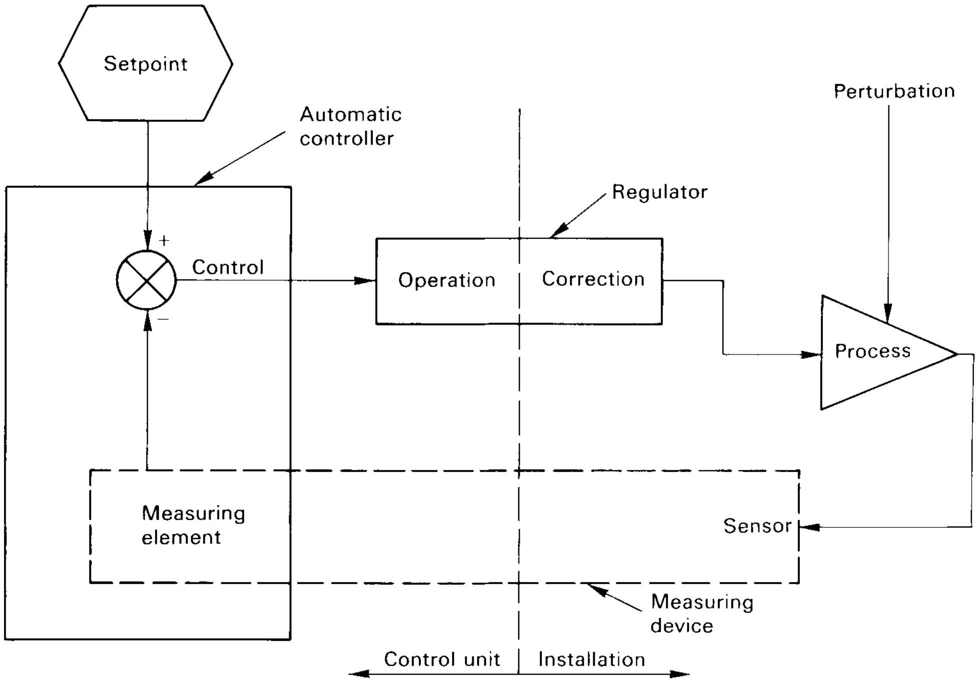


Fig. 14. Automatic closed loop control system.

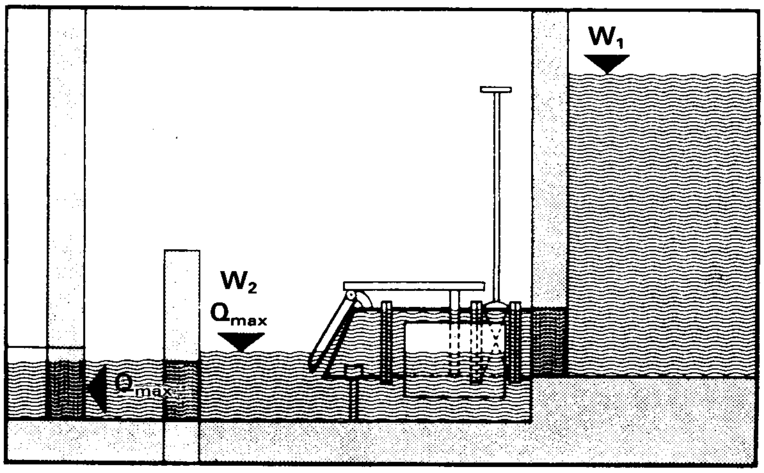


Fig. 15. Maximum flow control of a storage pond (Oswald Schulze, 1986).

In digital control systems the data acquisition of signals occurs at discrete moments of time and analog signals have to be converted into a digital form.

In discrete control systems the duration of the interval is important for the dynamic behaviour of the control loop. Some systems are discrete because of the application of instruments which provide only discontinuous information on the measured variable (e.g. radar systems). In chapters 5.2 and 5.3 the behaviour of continuous and discrete controllers is discussed in more detail.

5.1.3 SEQUENCE CONTROL

With sequence control the output variables of an open control system follow a predefined program. Sequence control can be divided into control with a fixed or with an adaptive program:

- fixed sequence control: the different output variables are changed due to a time schedule (e.g. fixed time-sequence control of pumps in an UDS),
- adaptive sequence control: the course of the program depends on the actual behaviour of the process and how the process is estimated to proceed.

A sequence control program can be very complex. Sequence control can very successfully be applied in RTC of UDS, preferably in combination with a matrix control strategy (Chapter 6).

5.1.4 BACKCHAINING

The control loop is the essential part of a closed control system. In the control loop the measured value of a controlled variable is compared with the value of the set point. Depending on this comparison the controlled variable will be adjusted.

The state of a UDS is continuously changing due to all kinds of external influences. Depending on the way these disturbances of the process are compensated, two principles of control can be distinguished:

- Feedback control (Fig. 16): the process variable to be controlled is measured. As soon as this value changes due to a disturbance of the process and differs from the set point value, the controller reacts in such a way that the deviation is compensated.
- Feedforward control (Fig. 17): the disturbance of the process is measured and its influence on the process is compensated by the controller. Hence, the controller must be able to predict the influence of the disturbance using a model of the process. Then it activates control ahead of time to avoid the deviations.

A feedback/feedforward controller is a combination of these two controlling principles (Fig. 18).

In backchaining, the controller action is limited to avoid over-compensation. In the extreme case, instability occurs when the controller reacts too fast on over-compensation. The dynamic behaviour of controllers is further discussed in Chapters 5.2 and 5.3.

5.1.5 INTEGRATION OF CONTROL

In general a process has several control variables. In a control system of such a multivariable process one can distinguish internal and external control loops (Fig. 11):

- Internal control loops are closed by conventional controllers. They control the variable of the process on the basis of a predefined set point. The controller determines the difference between set point and controlled variable and creates signals to the regulators such as pumps, motors, regulating valves etc. for corrective action.
- External control loops are closed by the operator. This person adjusts the set points of the internal control loops on the basis of observations of the process variables and other information.

A digital computer can be used in this system in several configurations:

- off-line: control with the computer outside the loop,
- on-line: control with the computer as a part of the loop,

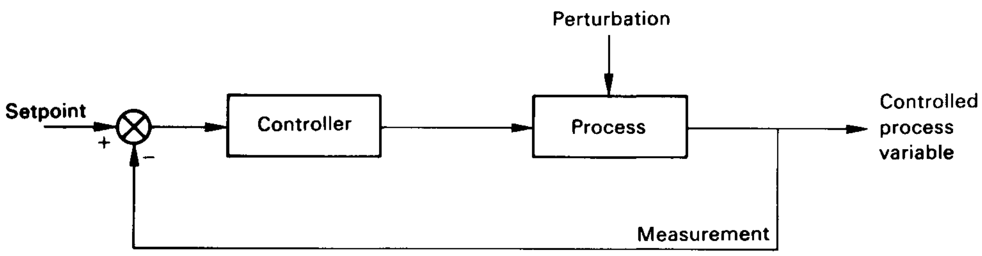


Fig. 16. Feedback control.

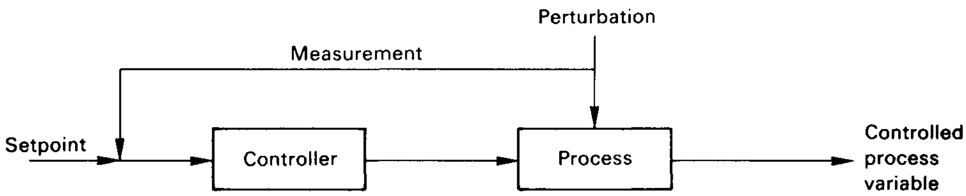


Fig. 17. Feedforward control.

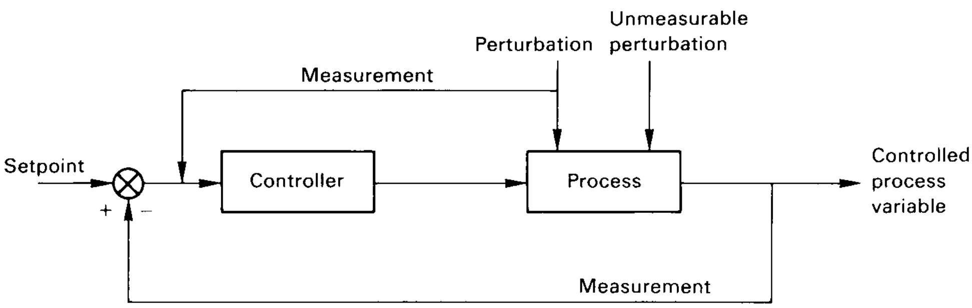


Fig. 18. Feedback/feedforward controller.

– in-line : control with the computer inside the loop.

In an off-line application the computer is not connected to the process at all. The computer determines the optimal set points for the operator on the basis of his observations of the process and additional information.

In an on-line application the transfer of information from the process to the computer is automatic. The computer 'advises' the operator in the determination of the new set points. In this way the computer can also be used for alarm scanning and data logging. After the occurrence of an alarm the operator can use the computer for further diagnostics or advice on possible controlling actions.

In the case of in-line application, one or more control loops are closed by the computer without intervention by the operator. This configuration can be subdivided into control loops with:

– supervisory control (indirect digital control), and
– direct digital control.

In these cases the function of the operator is replaced by the computer. In indirect digital control systems there is still a separation between conventional internal control and the digital external control system. In the direct digital control (DDC) system the internal control loops are also replaced by digital computers. The next step is to integrate both indirect and direct digital control where both internal and external control loops are replaced by digital computers.

5.2 Continuous controllers

Let us consider the regulation of the gate opening of a retention pond outlet to maintain constant outflow (Fig. 19). An additional gate might be located downstream of the pond outlet for fine-tuning. Whenever the gate opening is changed the flow shows a typical reaction. Based on the physical behaviour of the system (i.e. its differential equation) these reactions can be of a proportional (P), integral (I) or differential (D) type. The reaction can also be a combination of these types, including a time delay between regulator action and sensor reaction. These different controller types are discussed in the next sections.

The controller action is explained by the behaviour of the systems they control (i.e. integrating and differentiating processes). These system reactions can be correspondingly implemented in the controllers. Controller behaviour and system reaction should therefore not be confused.

The flow of information in an automatic control system is illustrated in block-diagrams, as shown in Fig. 20. In these block-diagrams the following variables are used:

– r: set point
– x: input variable
– y: output variable
– z: disturbance of the process
– H: transmission ratio = y/x
– s: d/dt

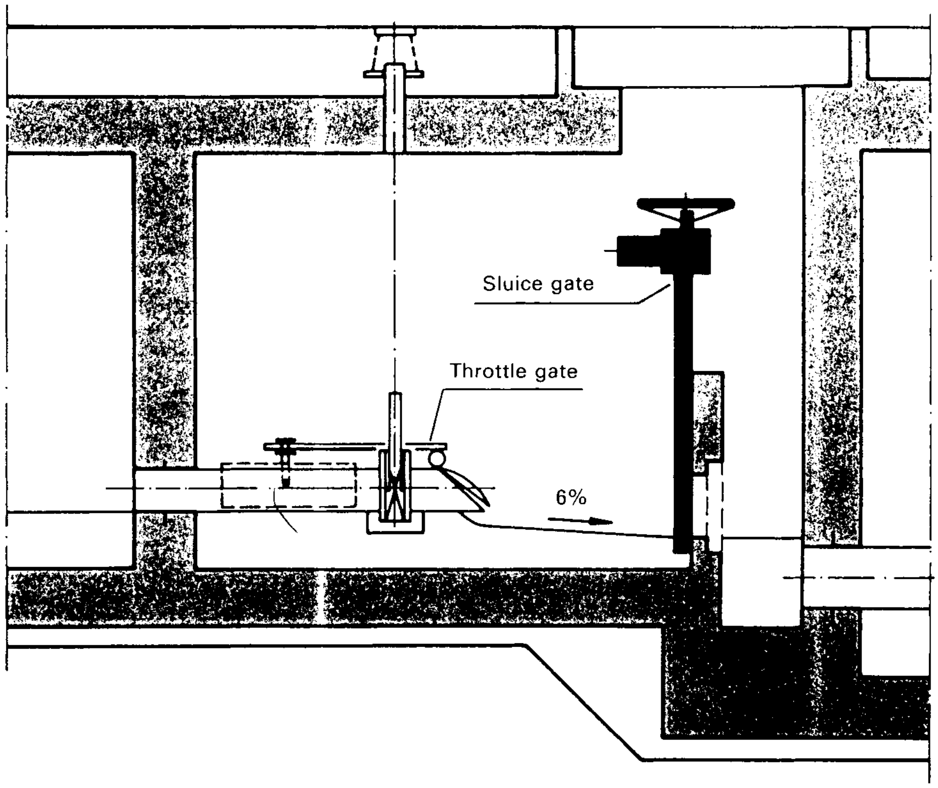


Fig. 19. Constant outflow regulation of a retention pond (Oswald Schulze, 1986).

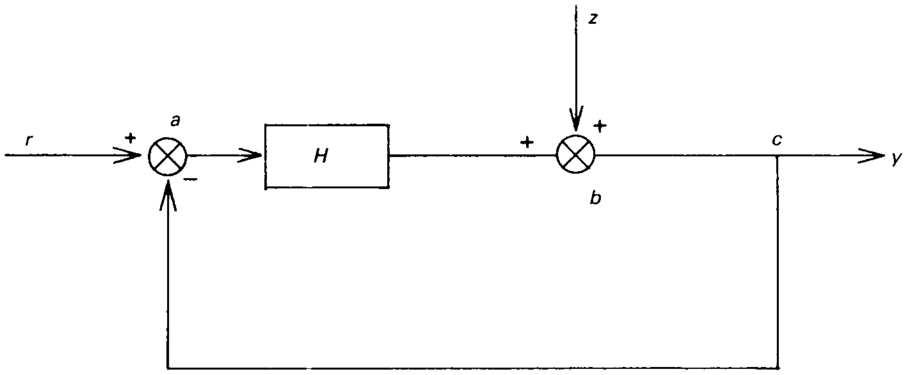


Fig. 20. Block diagram of controller (Cool *et al.*, 1972).

- a: subtraction node
- b: addition node
- c: any other node

Unless mentioned otherwise, all variables are time dependent. The transmission ratio determines how changes of the input variable of the controller are dynamically transformed into an output variable. The transmission ratio can be interpreted as a symbolic notation for linear differentiation with respect to time.

5.2.1 P-CONTROLLER

The simplest controller behaviour is that of a P-controller. Here the signal x to actuate the regulator is proportional to the difference between the measured variable and the set point (Fig. 21):

$$x = K(y - r)$$

The intensity of the controller reaction is given by the proportional gain K. Too low a K makes the controller slow, a value too high causes overcompensation of the controller, which may lead to instability.

A simple example of a P-controller is a float-actuated valve for the control of a reservoir level. The displacement of the float in the reservoir y (Fig. 22) causes a proportional alteration of the gate opening x:

$$\delta x = -K\,\delta y$$

The negative sign indicates that the valve is closing when the level is rising.

The disadvantage of a P-controller in a loop with pure P- behaviour is that, when the outflow of the reservoir increases (disturbance z), the level y will become lower, leading to an increase of the gate opening. In this way, the

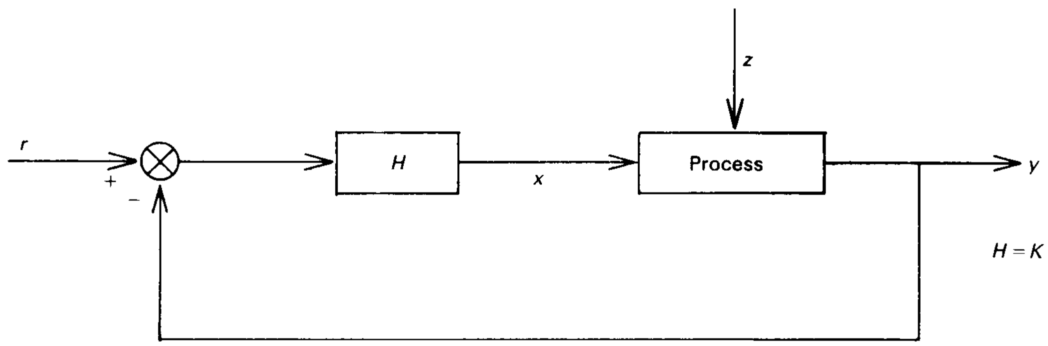


Fig. 21. Block diagram of a P-controller (Cool *et al.*, 1972).

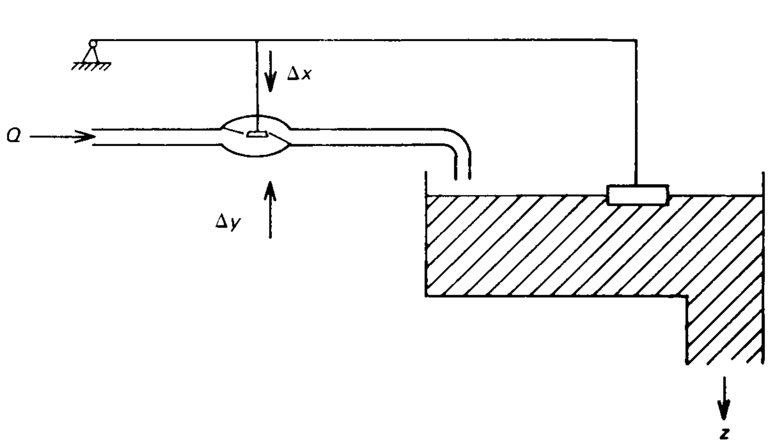


Fig. 22. P-controller (Cool *et al.*, 1972).

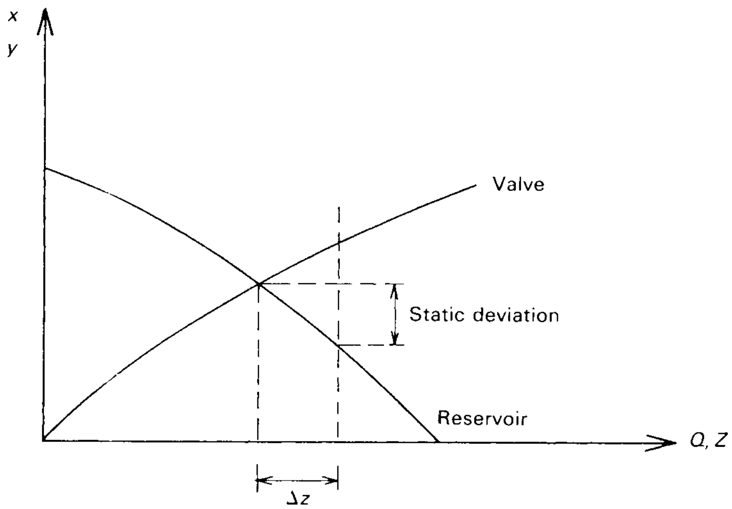


Fig. 23. Static deviation.

inflow Q will increase and a new equilibrium will be created, however, at a lower level. This means that deviations from the set point (offset or static deviation) cannot be avoided with a P-controller (Fig. 23).

5.2.2 INTEGRATORS

A simple example of an integrating system is the inflow into a reservoir (Fig. 24). Because of the fact that the inflowing quantity is equal to the storage amount in the reservoir we can write:

$$x\,dt = \mu A\,dy$$

$$dy/dt = (1/\mu A)x$$

The solution of this differential equation is:

$$y(t) = (1/\mu A)\int_0^t x\,dt + y_0 \quad \text{with } y_0 = y(t=0)$$

A system that reacts as a differential equation of the type above is called an integrating system or integrator. The transmission ratio can be computed as:

$$H = y/x = (1/\mu As) = (1/\tau_i s)$$

where $\tau_i = \mu A$ is the integration time constant. The system response of an integrating system can be determined by changing the input variable x in one of the standard ways (Fig. 25): impulse function, jump function or linear function. The system response of the integrator is also represented in this figure.

In Fig. 26 the proportional control of an integrating system is shown. The controller is transforming the level changes y into changes of the regulating valve. The reservoir acts as an integrator. The flow Q to the reservoir is proportional to the level changes y. The disturbances z_1 and z_2 disturb the desired relation between the level and the position of the valve. The disturbance z_1, for example, is a change of the outflow; the disturbance z_2 can be caused by suddenly adding a certain amount of water to the reservoir (jump function).

This feedback integrator behaves like a first order system with the following overall transmission ratio:

$$H = K(1 + (1/\tau_i s))$$

The reaction of the controller on a sudden change of the set point r and the disturbances z_1 and z_2 are illustrated in Fig. 27. It can be seen that there is no static deviation in the case of the disturbance z_2. However, the disturbance z_1 does create an offset of the reservoir level. Therefore, it is important whether the disturbance acts before or after the integrator.

The integrating action is a part of the process to be regulated (in this example: proportional). However, the integrating action can also be part of the controller itself, the I-controller. Then the controller reacts like an integrator. An I-controller reacts more slowly than a P-controller. However, it always forces the process back to the set point. The disadvantages of P- and I-controllers can be avoided by combining them into PI-controllers.

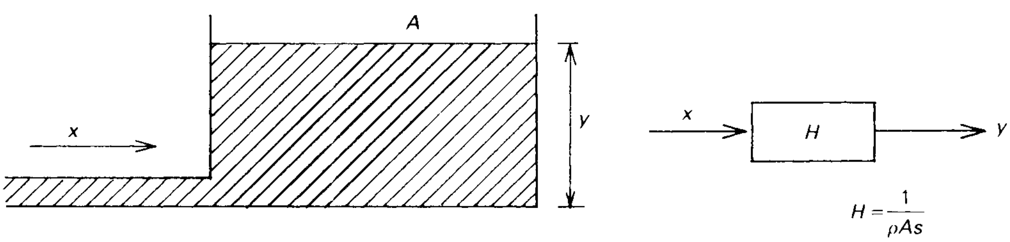


Fig. 24. Integrator (Cool *et al.*, 1972).

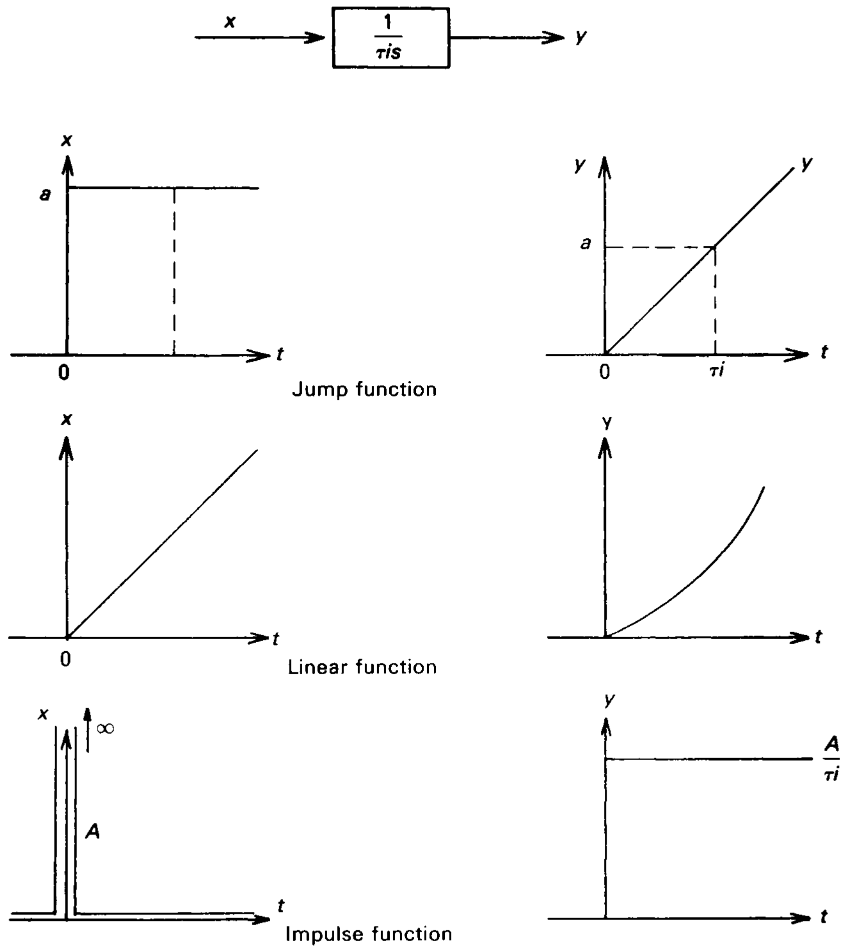


Fig. 25. System response of an integrator (Cool *et al.*, 1972).

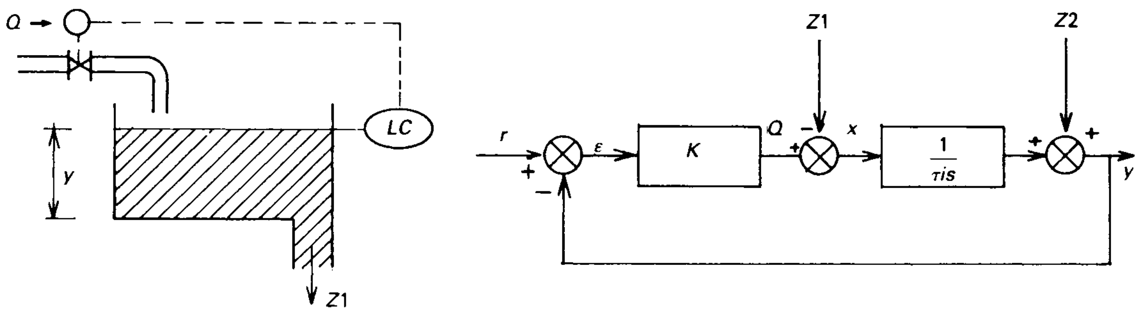


Fig. 26. Proportional control of an integrating system (Cool *et al.*, 1972).

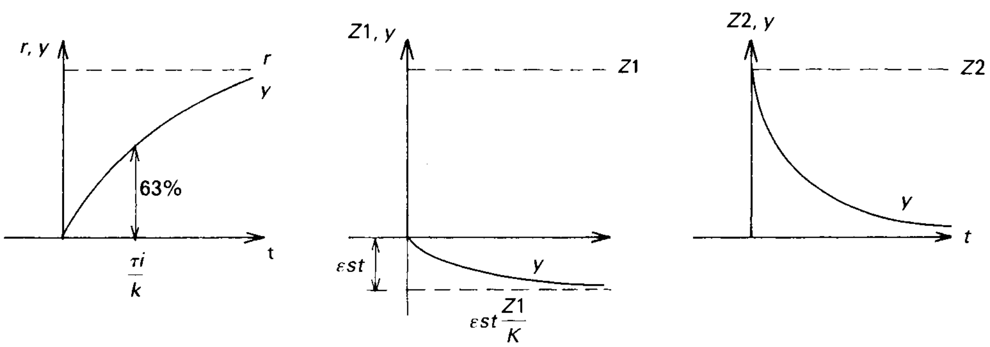


Fig. 27. System reponse of a proportional integrator (Cool *et al.*, 1972).

Many systems behave like a first order system, which can always be considered as a feedback integrator. A first order system returns to a new equilibrium after being exposed to a disturbance according to a negative exponential function. First order systems are very well suited for on/off control (see Chapter 5.3.1).

5.2.3 PD- AND PID-CONTROLLERS

In the example of the preceding chapter (Fig. 26), the controller is designed as a proportional or P-controller. The system itself acts as an integrating system. This integrating function can also be included in the controller together with the proportional behaviour. Thereby the controller acts as a PI-controller and can be used to control processes where no advantage can be taken from the integrating behaviour of the process. Neither a set point alteration nor a disturbance will cause the static deviation that can be observed in P-loops (Fig. 27).

Another type of controller is the PD-controller which acts as a proportionally controlled differentiator. A differentiating system behaves as shown in Fig. 28. The transmission ratio is:

$$H = \tau_d s$$

in which τ_d is the differentiation time constant. The proportionally controlled differentiator has the following transmission ratio:

$$H = K(\tau_d s + 1)$$

The differentiating action can be included in the PD-controller in the same way as the integrating action of a process can be implemented in a PI-controller. The PI-controller may have the advantage of little or no static deviation. However, the PD-controller shows a quick response with sufficient damping. A disadvantage of this quick response is that in cases of disturbances with high frequencies, the controller produces highly variable output signals. The resulting regulator action consumes much energy and, often more important, wears out much faster. Furthermore, other process variables might be additionally disturbed by the high frequency PD-action.

Disadvantages of single P-, I-, or D-action can be reduced by combining them into the PID-controller. By the combination of P-, I- and D- functions a standard controller is available which can be adjusted to all kinds of processes. The transmission ratio of a PID-controller is:

$$H = K(\tau_d s + 1) * (1 + (1/\tau_i s))$$

For the calibration of PID-controllers, real or simulated experiments can be executed. However, many standard rules are provided to quickly pre-adjust a controller to the process. For applications in RTC of UDS it is important to apply the following requirements to the PID-controller:

- quick response,
- sufficient damping,
- small static deviation.

If the controlled process is nonlinear (e.g. gate flow as a function of gate opening, channel flow as a function of water level) the controller parameters K, T_d, T_i are only valid in the vicinity of a reference point (e.g. a particular flow rate or water level). For other reference points other sets of parameters have to be found.

Once implemented, the behaviour of a controller has to be tested. If possible, full-scale experiments over the whole range of control variables have to be carried out to ensure that instability cannot occur. Otherwise, regulators would permanently be activated and wear out very fast. During routine operation, the initially selected control parameters can be fine-tuned to eventually reach optimium controller behaviour.

5.3 Discrete controllers

5.3.1 TWO-POINT CONTROLLER

Two-point or on/off control is the simplest, cheapest and, therefore, most frequently applied means of control. An advantage of this type of control is the simple corrective device needed. It has only two positions: on-off or open-closed.

An example is the two-point control of a pump filling a reservoir (Fig. 29). When the measured value (the water level) reaches a certain limit (low level) the regulator (pump) will switch on and the input signal of the process (pump discharge) obtains the maximum value. Also the output signal (water level) will rise. When the measured output signal reaches a high level, the regulator will switch off and the input signal becomes

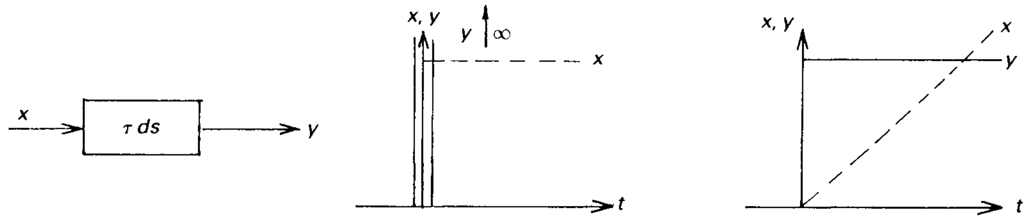


Fig. 28. Response of a differentiator (Cool *et al.*, 1972).

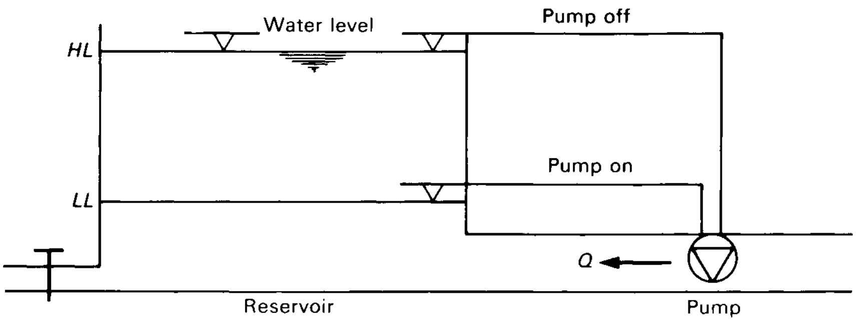


Fig. 29. Two-point control.

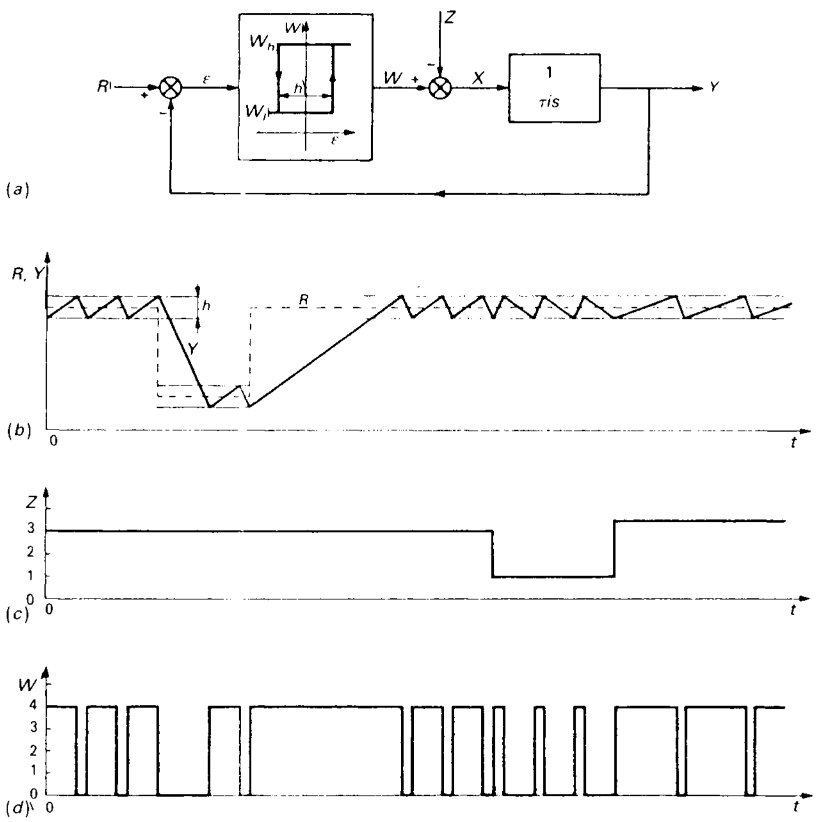


Fig. 30. System-dynamics of two-point control (Cool *et al.*, 1972).

minimum. Then the output signal will decrease again.

Because of imperfection in the regulator and the controller, the level will increase slightly above the high level and decrease below the low level. This effect is called hysteresis (h) and can be taken advantage of in order to reduce the switching frequency and to minimize the wear and tear of the regulator.

In Fig. 30 the dynamics of discontinuous control of an integrating system is shown. The system corresponds with Fig. 29.

5.3.2 THREE-POINT CONTROLLER

The on/off control mentioned in the preceding chapter has the disadvantage that frequent switching is necessary. This may cause problems when the frequency becomes too great. Therefore, three-point controllers have been developed. In the middle position of the controller the output signal is indifferent (zero) and in the other positions: maximum (+M) and minimum (-M), respectively. When the system is at its desired state, the output signal is zero and the regulator is inactive. In Fig. 31 the block diagram of a three-point controller is shown.

Besides the hysteresis the dead band (D) is also relevant. When D is chosen too large, the controller will behave indifferently. When D is too small, the positive effect of the three-point control will be reduced. A three-point controller has three operating conditions. However, the output signal of the middle position of the controller does not necessarily have to be zero. For instance, when pole reversing electrical pumps are used, the following operating conditions might apply: high speed (Q_HS), low speed (Q_LS), and zero. In Fig. 32 the application of a three-point controller for such a pump is shown.

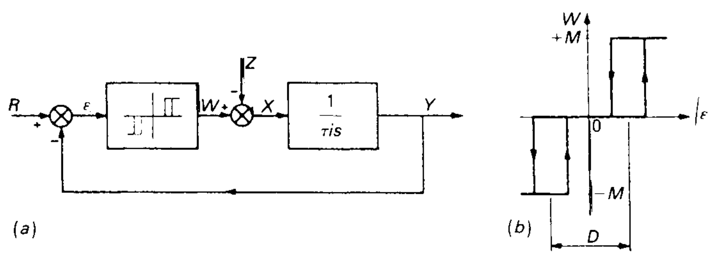


Fig. 31. Three-point control block-diagram (Cool *et al.*, 1972).

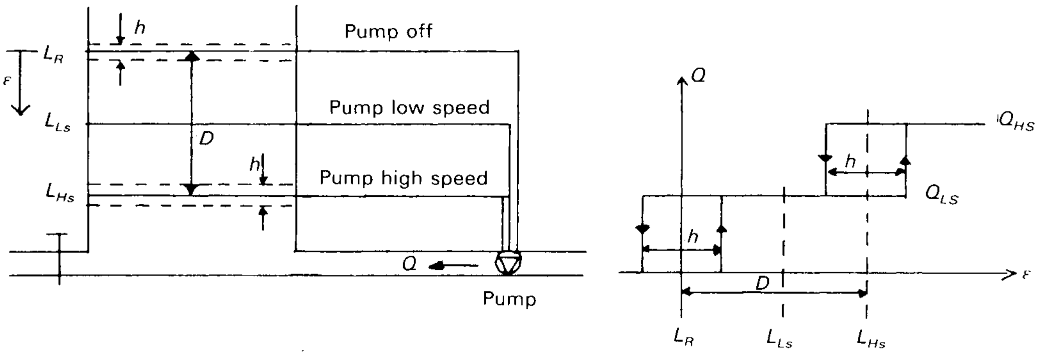


Fig. 32. Application of three-point controller to a high speed/low speed pump.

5.4 Summary, discussion and conclusions

Several types of control techniques are applicable in RTC of UDS. Closed loop control is the most common. Depending on the way control actions are executed and process signals are monitored, control systems can be divided into continuous and discrete control systems. For local control, continuous controllers can be applied as proportional (P)-controllers. In combination with a process with an integrator function, these systems act like first-order systems. The control performance can be improved by adding integrator (I) or differentiator (D) action to the controller. These so-called standard PID-controllers can be applied in many situations of RTC in UDS and can be adjusted in many ways to the different processes to be controlled.

Systems which already incorporate integrator functions, such as water storage, can be controlled very well by two-point controllers. To reduce switching frequency a three-point controller can be applied. High speed/low speed pumps in combination with three-point control is a typical example. Continuously speed-regulated pumps may use a PI- or a PID-controller as well.

In practice it is often very difficult to formulate the required control performance in advance, especially where the dynamics of the controller are concerned. Is a large deviation from the set point tolerable? If so, for how long? How often will it happen, etc?

In the design of a control system one has to rely heavily on experience gained in similar systems. If experience is lacking, the process dynamics have to be examined by simulating the processes and the controller. Also functional considerations such as efficiency, safety, or operational life have to be considered. It is obvious that good collaboration between control engineer and process (UDS) engineer is important from the very beginning of the design.

6. Control strategies

In the preceding section it has been shown how a controller adjusts a regulator to achieve minimum deviation of the regulated flow from the set point. This section discusses how to find these set points. A control strategy is defined as the time sequence of all regulator set points in a RTCS. Synonymously, the rules to specify such a time sequence can also be termed control strategy.

Figures 33, 34 and 35 demonstrate that the control strategy is a crucial feature of a RTCS. In Fig. 33 a single pond is operated to reduce peak stormflows. For fixed outflows (i.e. set points) only the second hydrograph is optimally alleviated. A varying set point would allow better performance in both the low and high inflow cases. In Fig. 34 a cascade of two ponds is to be operated to minimize overflows. On the left hand side of Fig. 35 a fixed set point strategy is applied: release as much as possible but no more than the downstream conduit capacity. Fig. 35 shows that the fixed set point strategy yields overflows whereas a better strategy with time-varying set points of pond outflows avoids overflows completely (right hand side).

The simplest control strategy is to keep set points constant (Fig. 36). For example, this option might be advisable for a regulated pond at the inflow of a treatment plant. One might also design a cascade of controllers, the output of a master controller being the set point of a slave controller. In Fig. 37 this arrangement is used to modify the set point of the lower pond outflow to avoid overflows.

In most cases optimum set points vary with each flow pattern. If these patterns would display periodical variability set point selection could simply follow a time schedule. A typical example is a water supply system where water demand shows a well known regularity. RTC of UDS, however, is control of transient stormflows and pollutant loads which show no regular pattern. Here, the optimum set points differ for every storm and even change within a storm. Hence, a flexible method has to be used to react to whatever transients will occur.

6.1 Operational objectives

Before the problem of determining the control strategy can be addressed, the objectives of the operation of the drainage system have to be specified. Mostly these are to avoid accidents, flooding, pollution through combined sewer overflows, and excessive operation and maintenance costs. It is not only useful to rank these objectives according to their priority but also to specify some 'ideal' operation and 'costs' if this optimum is not reached. The costs allow the evaluation of the performance of the control strategy with respect to every single objective.

Some objectives cannot be fulfilled at the same time – it is said that they are conflicting. For example, during a storm CSO can be reduced by storing storm sewage in the conduits (in-line), though at the higher risk of flooding. In these cases a trade-off between the conflicting objectives has to be defined and a best compromise strategy has to be found. Usually a much higher priority is given to avoiding flooding than to avoiding CSO. This again is much more important than to avoid O&M costs. Most important, of course, is safety for maintenance crews and town-dwellers. Hence, a trade-off between the various objectives is usually not applicable because the operational priorities are very distinct.

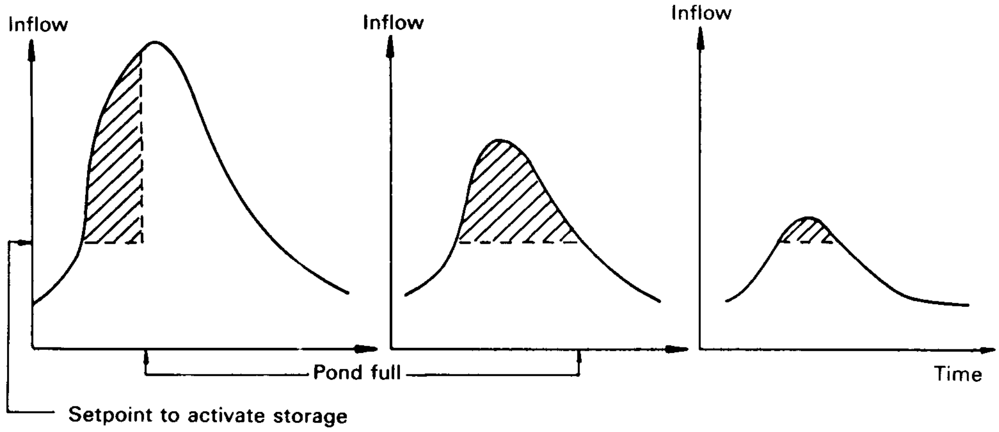


Fig. 33. Sub-optimal operation (left and right) of off-line storage pond with fixed set point.

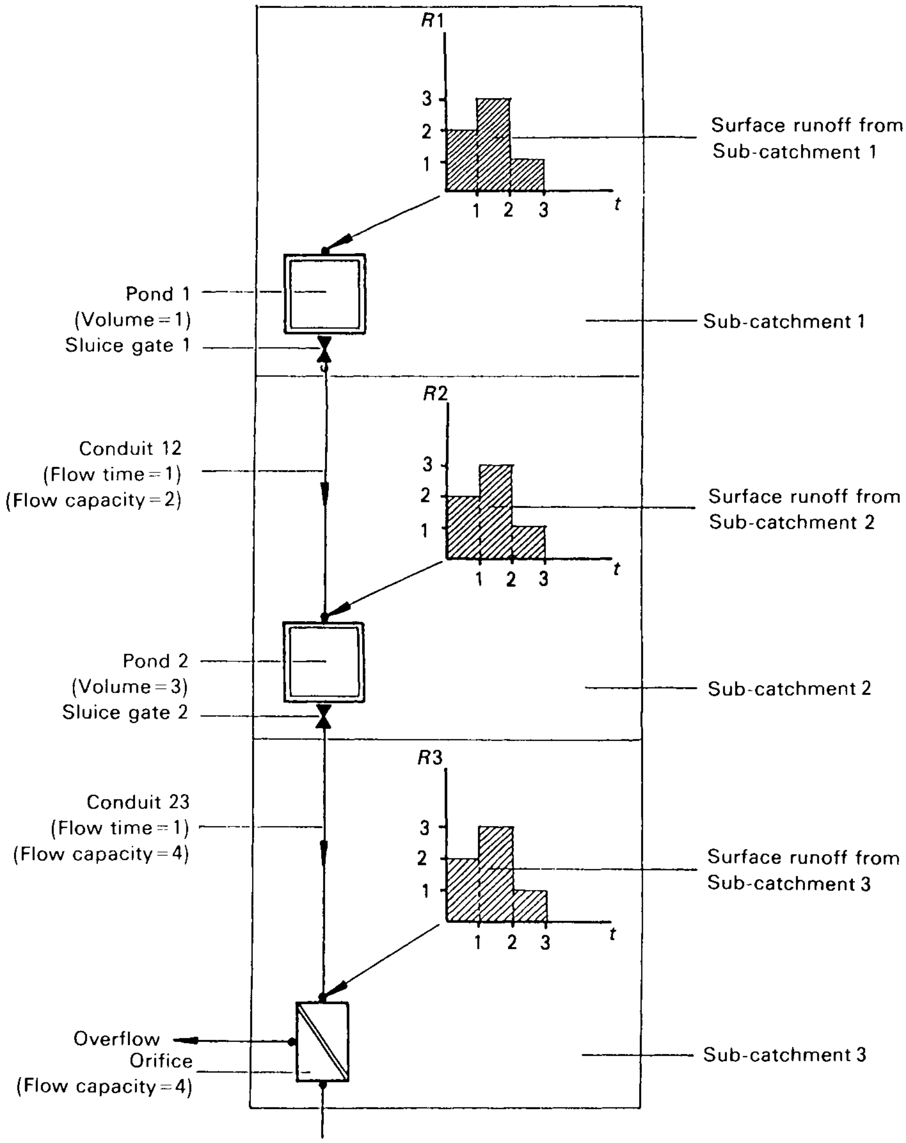


Fig. 34. Cascade of two ponds to be operated for overflow minimization.

6.2 Physical constraints

A control strategy has to be physically executable. In UDS this requires that pumping, flow through conduits, etc. cannot be greater than the physically possible rates (static constraints). Other static constraints which are less obvious but nevertheless important are the present (initial) and desired (final) state of the UDS (e.g. ponds empty, dry weather flow, etc.).

Additionally, the control strategy has to obey the physical laws of water motion in a drainage system, i.e. continuity and energy balances (dynamic constraints). For example, the dynamic constraint of a detention pond is:

(storage at time t+1) − (storage at time t) = (inflow during interval t) − (outflow during interval t)

A dynamic constraint of a conduit would describe the flow transport, e.g.

(upstream flow at time t−1) = (downstream flow at time t)

It should be noted that the latter example is a simplification of the underlying physics of the flow process. Because of nonlinearities of friction this flow routing equation is only a rough approximation. It is these constraints that make the problem of finding a control strategy complicated, especially if they change accidentally during a storm (e.g. blockage of conduit, defect of pump, etc.).

6.3 System loading

The physical capacities of a UDS are either known to the engineer or can be determined

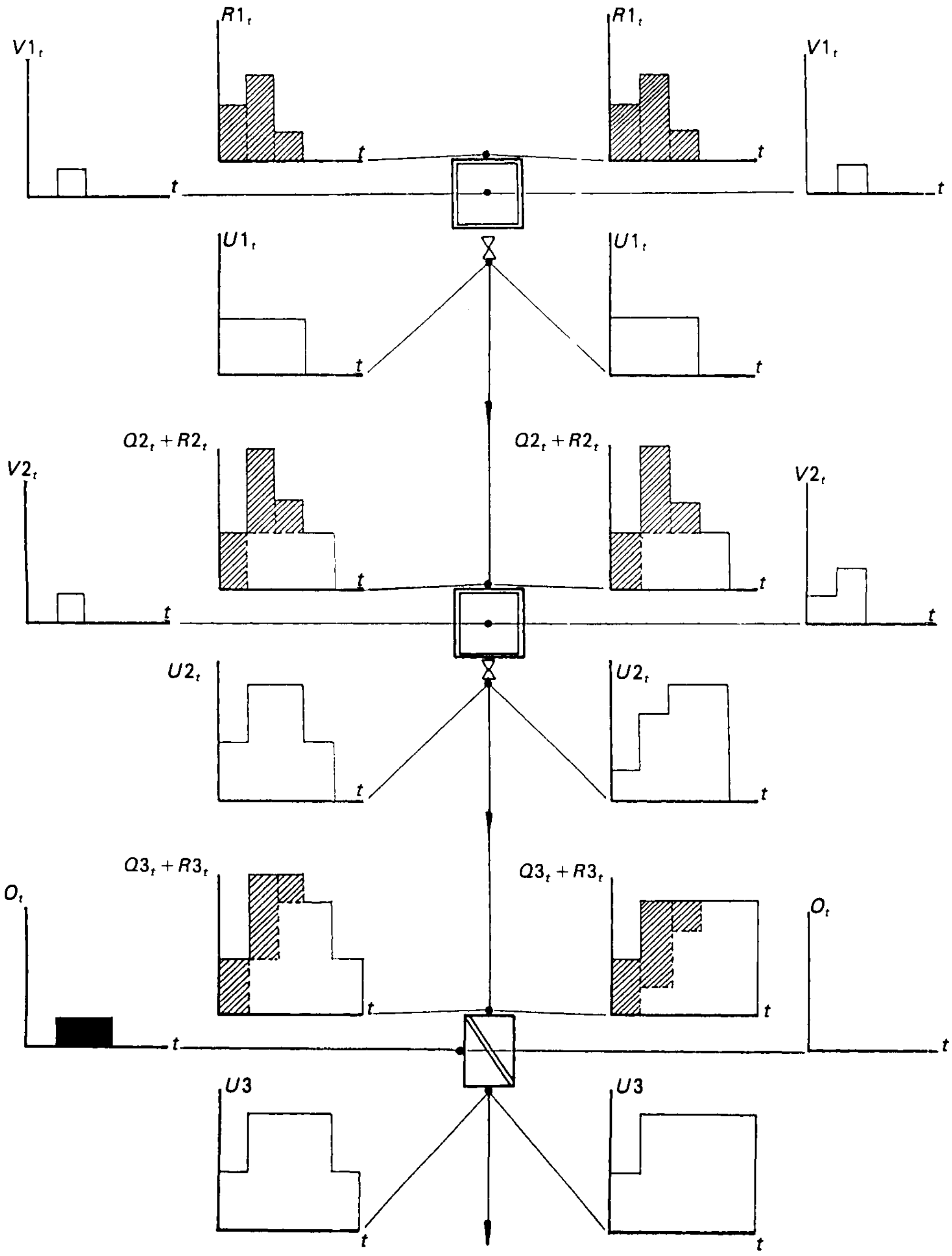


Fig. 35. Local control (left) and optimal global control (right) for cascade of two ponds.

with a sufficient degree of accuracy. The loading of the system, though, be it storm inflows or pollutant discharges, is more difficult to determine in real time.

Some knowledge of 'what will enter the UDS next' would be very useful information for the decision on how to control flows. It is also clear that the longer these forecasts reach into the near future the better a control strategy can be. Options to determine the input of a UDS are:

- flow and water level measurements in upstream sewers which allow reaction within the travel time of the sewage,
- rain measurements and application of rainfall/runoff models which extend the available reaction time by the flow concentration time on the surface of the catchment, and
- rain forecasts which would gain additional time depending on the forecast time horizon.

If none of this information is available the control strategy can only be of the fixed set point type.

Chapter 7 describes how UDS processes can be monitored. Section 4 discusses how they can be modelled. It is important to recognize that neither measurements nor computed flows are accurate. Measurements include measurement errors. Model computations include uncertainties which are due to unknown input, unknown parameters and model simplifications. It is therefore important to check

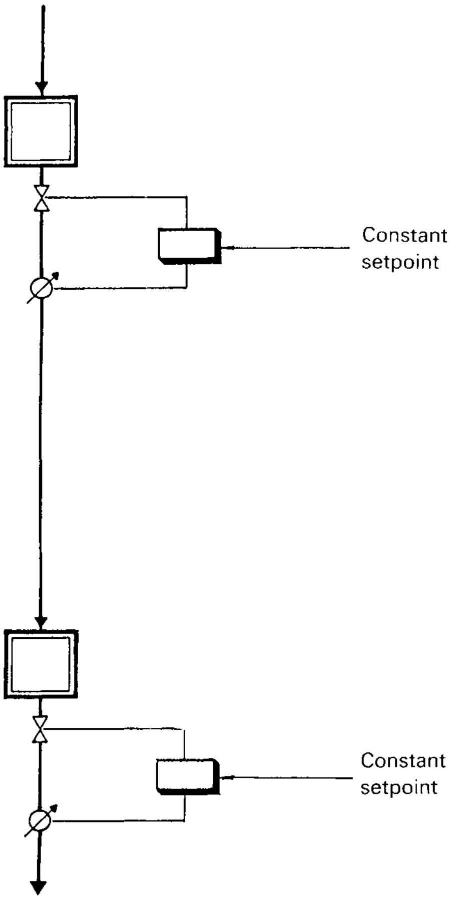


Fig. 36. Fixed set point control strategy (local control).

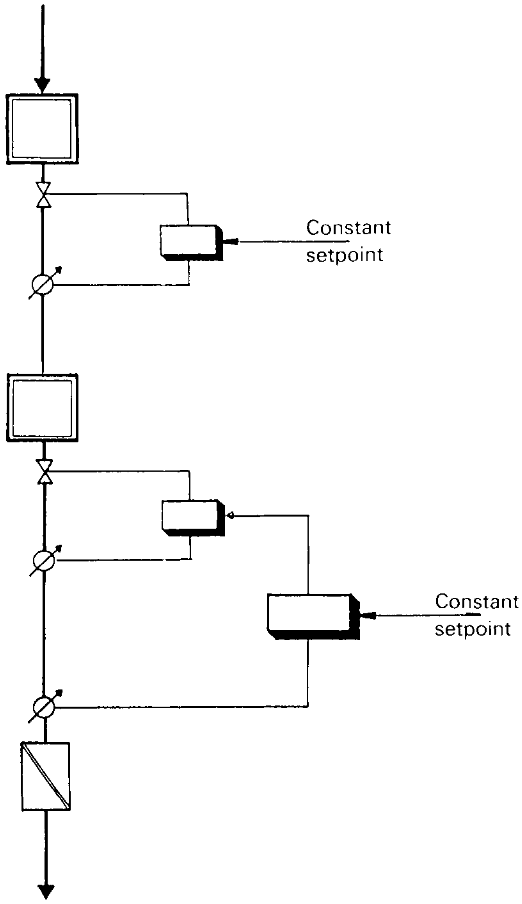


Fig. 37. Cascaded controllers (unit process control).

control strategies with respect to measurement and modelling errors. Practically speaking, control strategies have to be 'cautious' to avoid 'surprises'. These could be unexpected storm development, inflows from non-monitored tributary sewers, etc. Modelling uncertainty might be a reason why simulation is rarely applied on-line, during the ongoing process. Existing RTC strategies are rather based on measurements alone, but it is useful to develop them using off-line simulation of the UDS processes.

6.4 Solution techniques

6.4.1 OPTIMIZATION

The most rigorous approach to finding a control strategy automatically is to use mathematical optimization techniques (Fig. 38). Here, the problem is reduced to the minimization of an objective function ('cost function') subject to initial state constraints, state capacity constraints, control constraints, final state constraints, dynamic constraints, and non-negativity constraints.

One of the better known techniques is linear programming where all decision variables, i.e. state and control variables, are linear. Once a control problem is formulated as a linear programming problem (LPP) it can be easily solved with commercially available software packages.

For the example of Fig. 35, the LPP can be formulated so as to minimize the objective function (here: minimize total overflows)

$$\min \sum_{t=1}^{n} Ot$$

where n is the time horizon for which inflows can be specified and during which the desired final state shall be reached. The constraints which are not allowed to be violated at any time step t = 1,2,..,n are sub-divided into:

(1) Initial state constraints, (here: storage V, flows Q and overflow O are assumed to be zero)

$$V1_1 = 0$$

$$V2_1 = 0$$

$$O_1 = 0$$

$$Q2_1 = 0$$

$$Q3_1 = 0$$

(2) State capacity constraints, (here: maximum storage V and maximum flows Q)

$$V1_t \leq V1_{max} = 1$$

$$V2_t \leq V2_{max} = 3$$

$$Q2_t \leq Q2_{max} = 2$$

$$Q3_t \leq Q3_{max} = 4$$

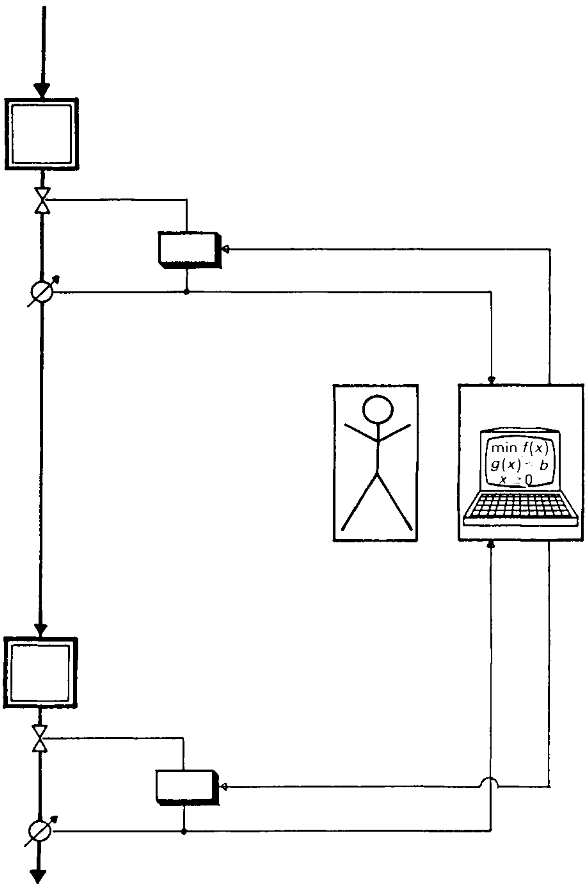


Fig. 38. Global control with set point optimization.

(3) Control constraints, (here: maximum pond releases U)

$$U1_t \leq U1_{max} = 2$$

$$U2_t \leq U2_{max} = 4$$

$$U3_t \leq U3_{max} = 4$$

(4) Final state constraints

$$V1_{n+1} = 0$$

$$V2_{n+1} = 0$$

$$O_{n+1} = 0$$

$$Q2_{n+1} = 0$$

$$Q3_{n+1} = 0$$

$$U1_{n+1} = 0$$

$$U2_{n+1} = 0$$

$$U3_{n+1} = 0$$

(5) Non-negativity constraints

$$V1_t \geq 0$$

$$V2_t \geq 0$$

$$O_t \geq 0$$

$$Q2_t \geq 0$$

$$Q3_t \geq 0$$

$$U1_t \geq 0$$

$$U2_t \geq 0$$

$$U3_t \geq 0$$

(6) The dynamic constraints require some simplifications of the flow process that is governed by the nonlinear St.Venant equations. Under the assumptions of:

- no backwatering,
- constant flow velocities,
- no attenuation of flow hydrographs within a conduit, and
- ideal performance of the downstream orifice with $U3 = Q3$ if $Q3 < U3_{max}$ and $U3 = U3_{max}$ if $Q3 \geq U3_{max}$;

the dynamic constraints are for:

- the mass balance in the upstream pond: $V1_{t+1} = V1_t + R1_t - U1_t$;
- the flow routing in the upstream conduit: $Q2_{t+1} = U1_t$;
- the mass balance in the downstream pond: $V2_{t+1} = V2_t + R2_t - U2_t + Q2_t$;
- the flow routing in the downstream conduit: $Q3_{t+1} = U2_t$;
- the diversion of overflows: $O_t = Q3_t + R3_t - U3_t$.

It should be noted that the dynamic constraints vary with every time step, because inflows R are never exactly known ahead of time. Hence, on-line optimization might have to be re-executed whenever actual inflows deviate too much from their forecasts. For given storm inflows and a time horizon of, say, n = 5, a solution of this problem is displayed in Fig. 35. In this case the control strategy is the hydrographs of the decision variables U (pond releases). These are the set points against which sluice gate flow rates for the two pond outlets are compared and actual outflows are corrected. It can be seen that the optimum control strategy avoids overflows completely. The local control with fixed set points (release maximum allowable pond outflows), on the contrary, yields overflows during two time intervals.

Other optimization techniques are discussed in detail in the literature. Applicable techniques include dynamic programming and its derivatives, derivatives of linear programming, and calculus of variation (Wenzel *et al.*, 1976; Bradford, 1977; Trotta *et al.*, 1977; Papageorgiou, 1983; Frerot *et al.*, 1986; Schilling *et al.*, 1986).

Common to any optimization technique are a number of difficulties:

(1) Operational objectives of an agency might be non-monetary, intangible, and/or conflicting. It is very difficult to aggregate all objectives into one single equation. Multiple objective optimization techniques, however, cannot be fully automatic. They require interaction with a decision maker to find best compromise (*Pareto optimum*) solutions.

(2) If a single objective function has been specified it is usually of a mixed integer/continuous, non-linear, and non-monotone type. Since powerful optimization techniques are not available for this kind of objective the function has to be further simplified.

(3) Flow routing has to be simplified to allow application of standard optimization techniques. This involves spatial and temporal aggregation, and linearization. The effects of these simplifications on final control performance, although probably not very important, have not been fully investigated yet.

6.4.2 SEARCH

Search is a technique that can be carried out intuitively (like a chess player does) or, similar to optimization, be formulated as a mathematical problem.

Usually one specifies an initial control strategy (e.g. the default fixed set point strategy). Based on additional information about the current state of the system and future input one would then try to change an appropriate control variable to gain some additional benefit (e.g. start pump earlier). If done automatically by a computer the strategy is changed for variables in a way that a prespecified **performance index** (i.e. objective function) gains maximum improvement. If no further improvement is possible it is assumed that an optimum strategy has been found.

Automatic search techniques require some insight into the search algorithm (e.g. steepest descent search, Newton-Raphson search, etc.) to reduce the number of required iterations. In practical applications such a large number of iterations might be required that the necessary computer time would not allow online applications. However, search techniques allow for a more flexible formulation of the objective function and the constraints (e.g. non-linear).

6.4.3 DECISION MATRICES

Decision matrices are a tool that, compared to optimization techniques, require extensive development work but allow for very fast online execution of control strategies. Essentially, control variables are specified in advance for all possible combinations of input and current state variables (Fig. 39). Therefore, if n state variables (e.g. pond storage, conduit flow) and p inflow variables (e.g. current inflow, next inflow, next but one inflow) are assumed, an $(n+p)$-dimensional matrix has to be specified. Each entry of the matrix represents the control decision which has to be executed for a given combination of state and input.

For the two ponds in Fig. 34, and given inflows and state data, a decision matrix such as Table 1 might be applied. From this matrix it is obvious that, for high input, flooding cannot be avoided. However, if one-step forecasts for the input $R2_{t+1}$ are available one can try to avoid upstream releases U1 if at all possible. Thereby, at least flooding at the downstream pond can be circumvented.

6.4.4 CONTROL SCENARIOS

Control scenarios are a simpler way to define a strategy. Possible states of the drainage system including forecasts of loadings are classified and control variables are given for each class. As with decision matrices, the problem is the sheer number of possible drainage situations which requires extensive development work beforehand.

For the example of Fig. 35 a strategy can be defined as a hierarchy of 'if . . . then . . . otherwise' statements:

(1) Strategy for pond releases U1:

If

$R1_t + V1_t + R2_{t+1} + V2_{t+1} \leq 7$

then

$0 \leq U1_t = R1_t + V1_t \leq 2$

otherwise

if

$R1_{+} + V1_t \leq 2$

then

$U1_t \leq 1$

otherwise

$U1_t = 2$

(2) Strategy for pond releases U2:

$0 \leq U2_t = R2_t + V2_t + U1_{t-1} - R3_{t+1} \leq 4$

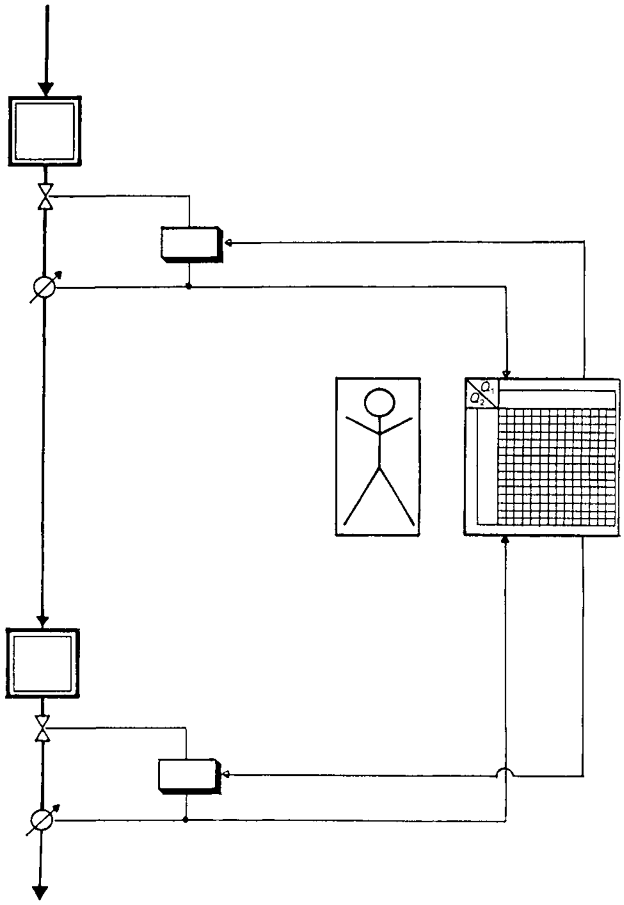


Fig. 39. Global control with decision matrix.

Table 1 **Decision matrix for the control of two stormwater ponds (V-storage, R-inflow, U-outflow)**

	V1t/V2t							
R1t/R2t+U1t−1	0/0	0/1	0/2	0/3	1/0	1/1	1/2	1/3
0/0	00	01	02	03	10	11	12	13
0/1	01	02	03	04	11	12	13	14
0/2	02	03	04	04	12	13	14	14
0/3	03	04	04	04	13	14	14	14
0/4	04	04	04	04	14	14	14	14
0/5	04	04	04	*04	14	14	14	*14
1/0	10	11	12	13	20	21	22	23
1/1	11	12	13	14	21	22	23	24
1/2	12	13	14	14	22	23	24	24
1/3	13	14	14	14	23	24	24	24
1/4	14	14	14	14	24	24	24	24
1/5	14	14	14	*14	24	24	24	*24
2/0	20	21	22	23	20	21	22	23
2/1	21	22	23	24	21	22	23	24
2/2	22	23	24	24	22	23	24	24
2/3	23	24	24	24	23	24	24	24
2/4	24	24	24	24	24	24	24	24
2/5	24	24	24	*24	24	24	24	*24
3/0	20	21	22	23	*20	*21	*22	*23
3/1	21	22	23	24	*21	*22	*23	*24
3/2	22	23	24	24	*22	*23	*24	*24
3/3	23	24	24	24	*23	*24	*24	*24
3/4	24	24	24	24	*24	*24	*24	*24
3/5	24	24	24	*24	*24	*24	*24	*24

* Flooding cannot be prevented.

6.4.5 HEURISTICS

Heuristic methods to find a control strategy are based on experience of the operating personnel. Here, an operator would either directly actuate the regulators (Fig. 40), specify only the set points of each regulator (Fig. 41) or even use an interactive flow simulator as a decision aid to find an appropriate control strategy (Fig. 42). Heuristic control has the potential to use sources of information that are not accessible to a computer (e.g. intuition, view out of the window, phone calls). In case of emergency an operator can immediately seek assistance, advise maintenance crews, etc. An experienced operator will probably carry out near-optimum control. He disregards (like a good chess player) all control options that are possible but not advisable.

Heuristic control also has serious drawbacks. Once an operator leaves his job his experience will also be gone. His successor will make mistakes all over again. Experience with stormwater RTC can only be gained slowly. It is raining approximately 5% of the time. An operator spends approximately 20% of the time on his job. Hence, only during 1% of the time is he really exposed to a stormwater RTC problem. Unless his job is integrated in treatment plant operation, three to four operators working in shifts have to be educated, trained, and paid just for stormwater operation. In conclusion, there are arguments in favour of automatic systems control.

6.4.6 EXPERT SYSTEMS

Recently, an attempt has been made to apply artificial intelligence to decision problems with so-called **expert systems** (Fig. 43). With an expert system it is programmed how experience is gained and how this experience is applied for decisions such as the specification of RTC strategies.

An expert system uses known information about the system, its operational state and precisely described reasoning processes to retrieve (or produce) new and previously unknown information about the system. For the development of a control strategy in real time one needs to specify the state of the flow process (past, present, and possibly future) and the goals to be reached.

In an expert system three knowledge levels have to be distinguished. Level 1 concerns knowledge about the state of the UDS to be dealt with (basis of facts). Level 2 is knowledge about how the desired information is to be derived from the actual state. These are the production rules. Level 3 is the interpreter which decodes these rules and applies them to each particular state of the system to allow consequences to be drawn.

For the development of a RTC strategy, level 1 knowledge is derived from the results of simulation models and measurements. Level 2 knowledge corresponds to the operator who, in real cases, proposes a solution and applies it. This is the expert's knowledge which

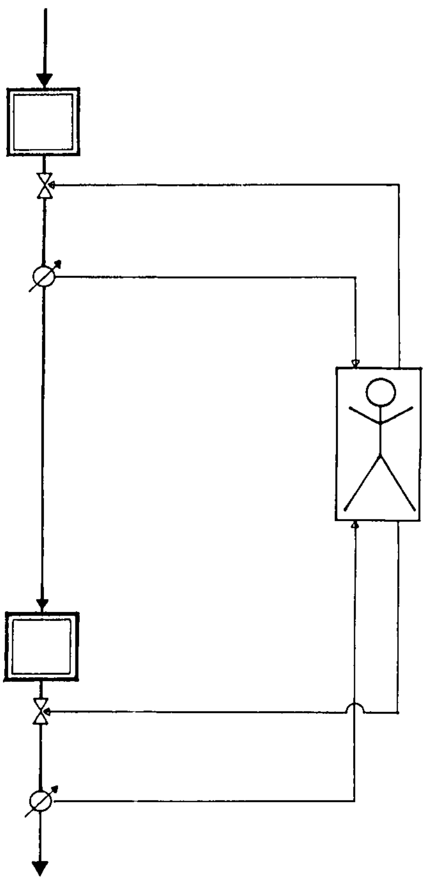


Fig. 40. Manual global control.

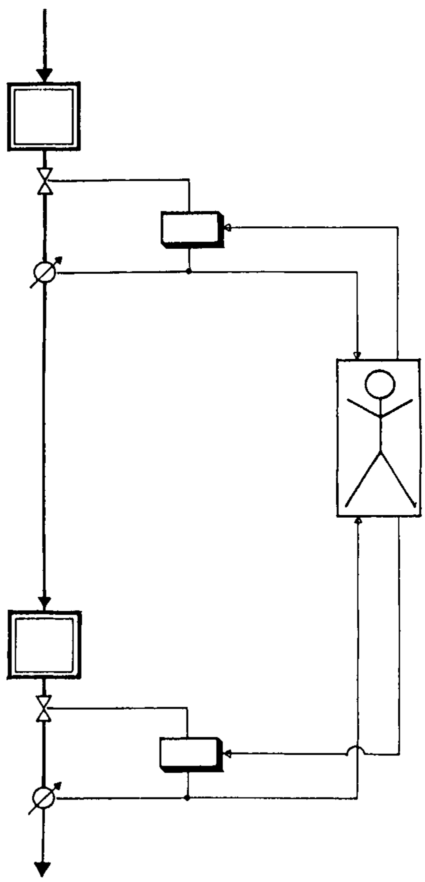


Fig. 41. Supervisory global control.

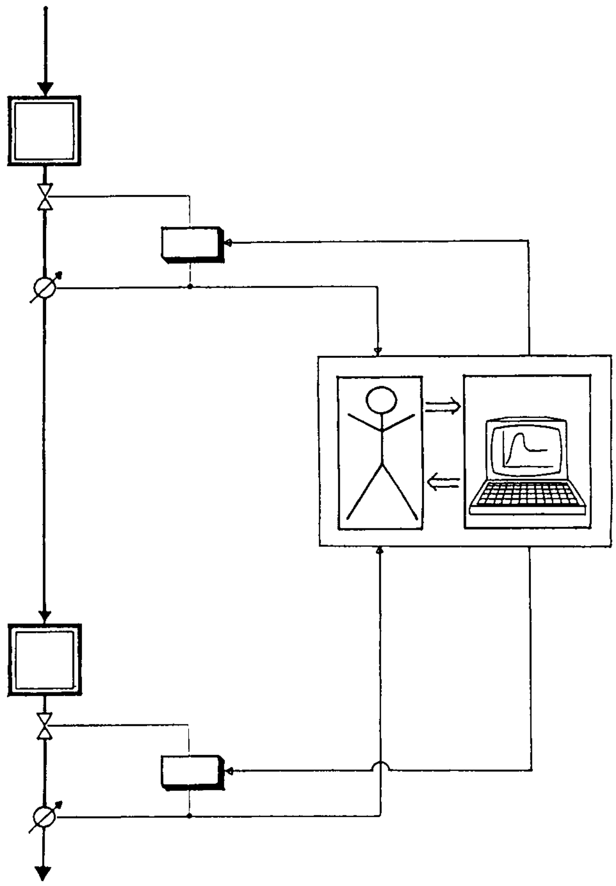


Fig. 42. Global control with decision aid system.

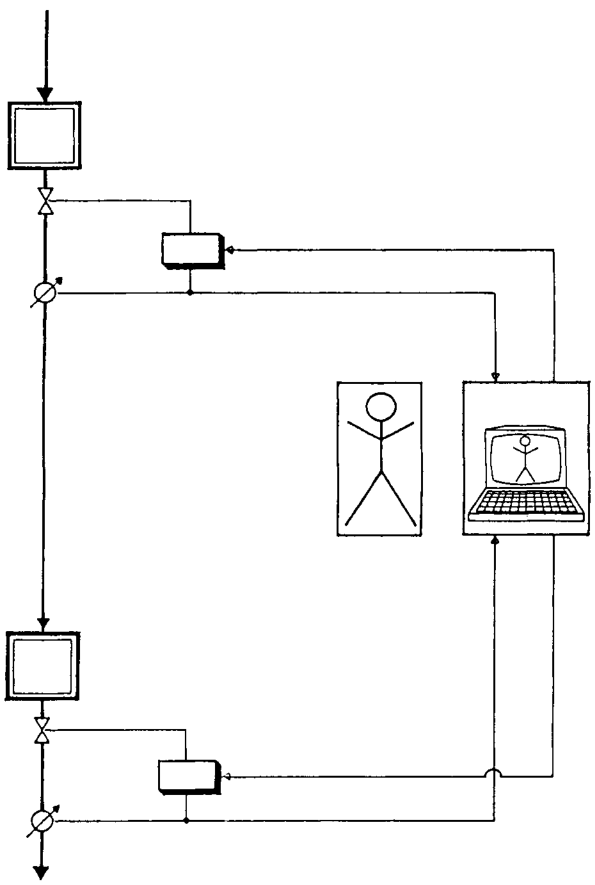


Fig. 43. Global control with expert system.

gives its name to the methodology. In opposition to optimization techniques, the purpose of finding the best solution is replaced by the one of finding a good solution or an acceptable solution. Level 3 knowledge deals with the actual mechanisms involved in the reasoning process and how it is to be translated into computer programs.

Ideally, a self-learning expert system is obtained which should be able to accumulate more experience than any human being in his life. In fact, the basis of rules cannot only be used to determine the strategy, but also to evaluate the rules that lead to the strategy, analyse them in relation to the operational situation and eventually come up with more appropriate rules (meta rules).

Expert systems have great flexibility in formulating different scenarios in that quantitative (e.g. m^3/s flow) and qualitative (e.g. heavy rain), deterministic (e.g. storage full) and probabilistic information (rain likely) can be combined. If subjective statements are to be included, obviously the expert system can only be used interactively with an operator. Expert systems are extremely application oriented and hardly transferable to other RTCS. In fact, their name includes the idea that the control decisions are not found through a model of the physical system but through a model of an expert (here: the operator).

6.5 Summary, discussion and conclusions

In a typical RTCS, pumps, sluice gates, weirs, etc. have to be operated to store flows in ponds and route them to treatment and receiving waters. The major objective in the operation of these regulators is to avoid flooding while minimizing CSO and O&M cost. It is particularly undesirable to let flooding or CSO occur if the system has idle transport or storage capacities at the same time. Proper operation should ensure that this does not happen.

Neither static flow restrictors (e.g. orifice) nor locally controlled regulators (e.g. vortex valves, float regulated gates) can guarantee good systems performance. This would only be achieved if each regulator (e.g. sluice gate) is operated in view of the flow process in the whole system. This operational mode is termed global control. Global control allows flexible reaction with respect to every operational situation since the set points of the control loops can be continuously adjusted with respect to the actual state of the UDS.

The time sequence of the set points of all regulators in a RTCS is termed 'control strategy'. The determination of a control strategy can be either automatic or manual. The strategy can be found through mathematical optimization, search, decision matrices, control scenarios, trial-and-error (heuristically), or through a self-learning expert system. This can be done either during the ongoing flow process (on-line) or beforehand (off-line). After the control strategy has been defined it is executed by controllers which are usually distributed in the field at the regulator sites.

In most existing RTCS, operators adjust regulator set points based on their experience. This control mode is called supervisory control. It is flexible in that operators can use any kind of information that is available. They react flexibly in unusual situations and can discard control strategies that 'would not be successful anyway'.

The determination of a control strategy requires the specification of the operational objectives, i.e. desired state of the system and priorities and how to evaluate deviations from this target ('costs'). While this is mandatory for strategy optimization it is at least useful for other methods of finding a strategy. Problems arise since most of the operational objectives in a UDS are non-monetary, intangible, and/or conflicting and therefore difficult to define.

The decision variables in any control system are physically constrained by both capacity limits and the laws of water motion. Whereas the formulation of capacity constraints is fairly straightforward, the hydrodynamic constraints usually incorporate a simplification of the governing physical laws. The robustness of the control performance with respect to these simplifications has to be checked by either modelling the controlled process with a detailed (and more realistic) model or by careful 'fine-tuning' in the real UDS.

The better the inflow volumes and pollution loads are known in advance, the better the process can be controlled. It is desirable to know future inflows as accurately as possible for the whole control horizon. The control horizon is reached when the system is back to its desired (e.g. initial) state. In a UDS this control horizon is the remaining storm duration plus the time required to empty the system through the treatment plant. Currently available rainfall and rainfall/runoff models may yield inflow forecasts which are considered to be not accurate enough. It has to be evaluated how inflow forecasting errors affect the quality of the optimized control strategy and, hence, in which cases inflow forecasts should be used.

7. Hardware elements of real-time control systems

7.1 Sensors

THERE is a long list of parameters and variables which the UDS engineer would like to use for controlling the sewer system. The intention, however, to use all these parameters cannot be realized. Many of them are not easily observed or determined. Furthermore, the allowable time to determine them for RTC purposes is usually too short. However, the already existing successful applications of RTC in UDS show that there are enough parameters which can be measured and monitored.

7.1.1 RAINFALL

Since the ancient high cultures the amount of precipitation has been recorded. Statistical analysis of this data shows relations between rainfall duration, frequency and intensity. A number of reliable rain gauges (pluviographs) have been developed which can also be used for remote data transmission. Thereby, rainfall can be used as a parameter for RTC.

A number of proven systems are operating. One is based on the electronic counting of raindrops collected by a calibrated funnel. By means of these devices the local precipitation can be measured for smaller intensities down to 0.005 mm/min. A heater, which has to be regulated by a thermostat, ensures operation even for temperatures below freezing. Since the rain drop counter is not applicable for high intensities it is often combined with a tipping bucket counter. After passing the drop counter, the rain water fills a small bucket which tips over when filled, empties and fills up again. A light barrier detects the tipping motions and an electronic device converts the signal into pulses (e.g. 1 pulse = 0.1 mm precipitation) (Fig. 44).

Another principle of rain intensity measurement is applied with radar. A radar transmitter sends out brief electromagnetic impulses which are partially reflected by the rain. The reflected microwaves are received by an antenna and further processed. From the direction and the travel time the location of the rainfall can be determined. The intensity of the reflected impulses is a function of the intensity of the rain.

Radar data have become available for operational purposes in many industrialized countries. This system can be of great assistance for rainfall forecasts, especially in large catchment areas, because it gives a picture of the areal extent and velocity of storms. Storm forecasts allow the determination of a control strategy even before the storm hits the catchment. As an example, the Detroit Metro Water Department (DMWD) continuously receives radar data provided by the United States National Weather Service. The radar covers the surrounding area at four different resolutions, of which the lowest provides a display reaching as far as Chicago in the West and Toronto in the East. Other examples are the weather radar system covering large parts of England and Wales or the Trappes radar which is used in the Seine-St-Denis RTCS.

7.1.2 WATER LEVEL

The water level is the most important variable to be measured in RTCS. It allows the computation of sewer flows in a drainage system. It is of further importance for quality considerations as long as it is not possible to measure pollution parameters without long time delays. The water level also provides information about the storage in a sewer or in a pond (being used or not), about necessary commands to regulator or outfall gates, weirs, pumps, etc.

A large number of different systems is offered, some of which are applicable in wastewater and sewer systems. The following criteria should be considered before installing level sensors:

- reliability,
- maintenance,
- resistance against aggressive substances,
- contact with wastewater,
- calibration,
- accuracy.

Some measuring principles, suitable for level monitoring for real-time control, are described below. A pressure sensor is submerged in the wastewater. The output signal is proportional to the water level above the probe. Pressure level sensors consist of a transducer (sensor) and an electronic unit. The transducer has to be mounted close to the bottom of the channel or the pond. In most cases capacitive pressure transducers or piezo-resistive transducers are used. Both of them convert the hydrostatic pressure of the liquid level into an electrical signal. This signal is electronically standardized and represents the level, usually displayed in percent of maximum stage.

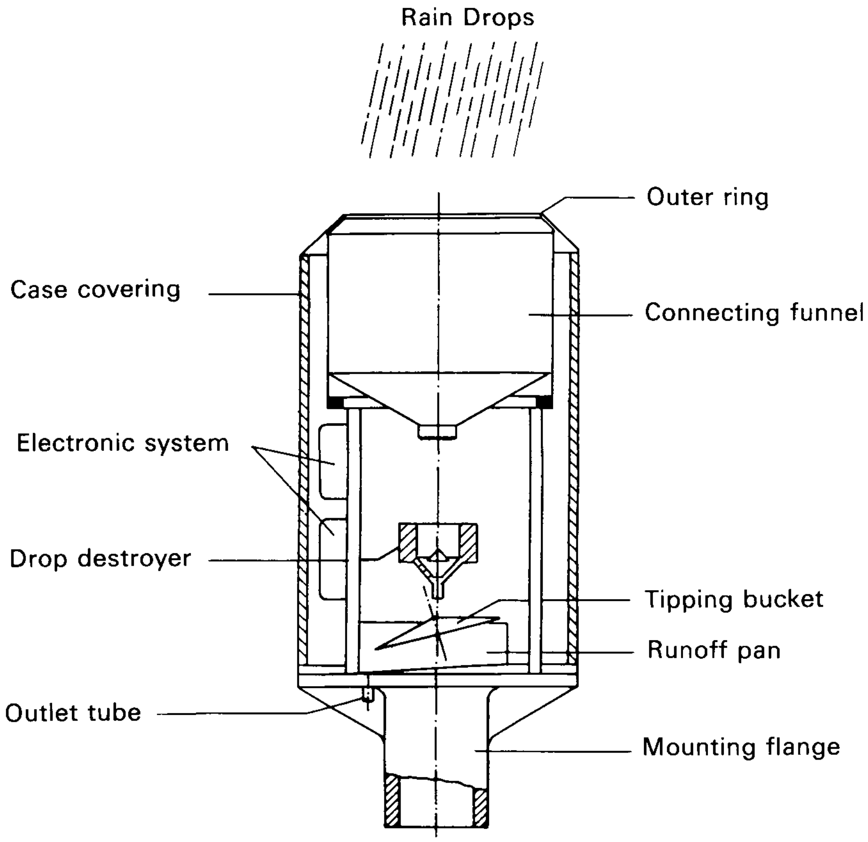


Fig. 44. Rain gauge with drop counter and tipping bucket (adapted from Thies, 1983).

Ultrasonic level monitors typically use two basic components: the ultrasonic sensor mounted well above the waste water and the electronics enclosure, usually mounted outside the sewer and connected to the sensor by wire. A transmitter sends out brief bursts of ultra high frequency sound. The sound waves are sent as highly focused beams directed at the surface of the water. They are reflected and the echoes are detected by a receiver. The time required indicates the distance from the sensor to the water surface, which again is used to determine the stage level (Fig. 45).

Another pressure system is the so-called 'bubbler' system. It consists of a little compressor which produces pressurized air. A constant air flow rate is released through a small pipe to the bottom of the tank or sewer. The pressure to overcome the hydrostatic counterpressure is measured. The system is influenced by the density of the liquid and the velocity of wastewater flow. Care has to be taken to prevent leaks in the piping and clogging of the pipe outlet (Fig. 46).

For simple on/off control, limit switches are applied (e.g. floating, conductivity probes, capacitive probes, ultrasonic limit switches). These switches allow for the detection of discrete water levels only.

7.1.3 FLOW

Direct measurement of the flow rates in partially filled sewers is very difficult. Combined water level and flow velocity are used for a continuous measurement of flow instead. The measurement of the water level is done as described above. If backwatering can be avoided and good information about slope, size and roughness of the sewer is available, the level can be transformed into flows by means of flow formulae such as the Manning equation. The accuracy of measuring the flow in this way is limited to usually not less than about 10% error.

Better results can be achieved by the installation of defined gauging sections in the sewer system in which supercritical flow is enforced. Thereby backwater is prevented and level-flow conversions can be rather precise (3% error). Various flumes are used for this purpose (Fig. 47).

If wastewater flows in a completely filled pipe other methods of metering are applicable. Electromagnetic flow meters based on the Faraday principle of induction can be applied. Extreme accuracy is attainable over a wide range of flow rates. The magnetic flow meter imposes no obstacle to the flow (Fig. 48).

With a sonic flow meter, ultrasound pulses pass the liquid to be metered at a 45 degree angle into the direction of flow. The travel time of the sound represents the inherent speed of sound within the liquid plus a contribution due to the flow velocity. A simultaneous measurement in the opposite direction represents the inherent speed of sound within the liquid minus the same contribution due to flow

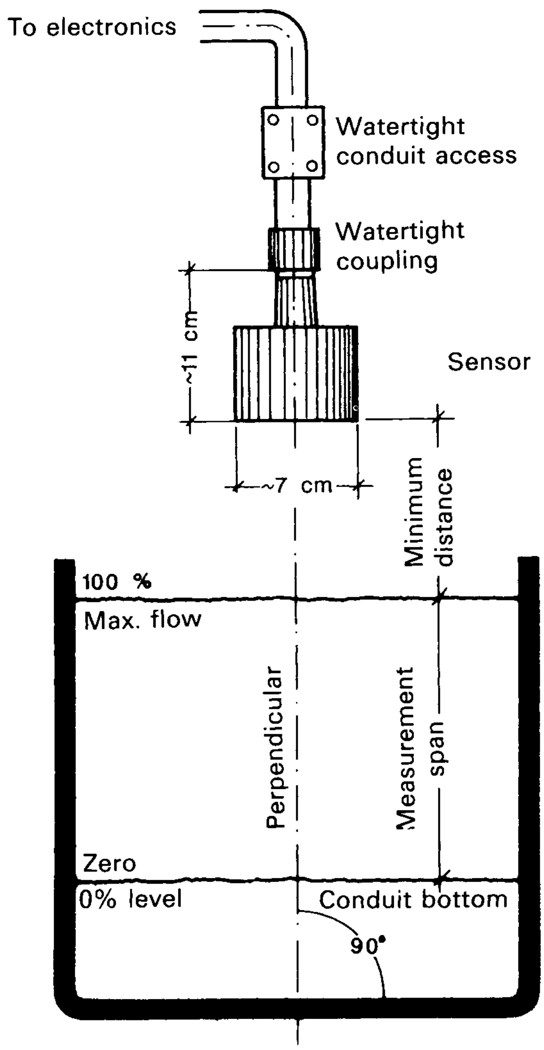


Fig. 45. Ultrasonic level monitor (adapted from Wesmar, 1987).

velocity. The difference is proportional to the flow velocity, independently of the specific liquid being metered (Fig. 49).

7.1.4 POLLUTANTS AND WATER QUALITY PARAMETERS

Waterborne pollutants and water quality parameters are significant for the influence of discharges to the receiving waters. Unfortunately there are no reliable instruments for on-line measurements of important pollution and water quality parameters in sewer systems. Recently, a short term (3 min) BOD sensor was developed but experience of it within RTC of UDS is not known. Investment cost is about tenfold of a level sensor which might be considered too expensive in relation to the information gained. Despite these problems, it is recommended to undertake accompanying quality controls off-line. This data can be used to simulate pollution transport and to ensure the effect of RTC with respect to pollution control.

7.2 Regulators

The best known regulators for combined sewer flows are pumps. Wastewater pumps are the most flexible but also most expensive flow regulators. Other remotely controllable regulators in UDS include:
- gates,
- weirs,
- air regulated siphon weirs,
- air regulated inverted siphons,
- valves, and
- inflatable fabric dams.

Regulators in CSS are often very large and custom designed. However, some basic principles are common to all successful designs:
- Regulators are fail-safe designed, in that malfunction of vital parts results in an acceptable functional decline of the system ('graceful degradation'). For example, sluice gates would have bypasses, weirs would move into the lowest position in case of a power failure.
- All parts exposed to sewage and the sewer atmosphere are drastically simplified and corrosion resistant. Preferable material is stainless steel. Cast iron, aluminium, and appropriate plastic materials are acceptable.
- Sensitive parts are placed in an appropriate environment, i.e. extra dehumidified vault for hydraulic and electric machinery, extra dehumidified and heated vault for transducers, telemetry equipment.
- All parts of a regulator station (including gates, sensors, motors) are accessible, maintainable, and exchangeable.
- Vital functions of regulators can be remotely supervised from the control centre.

7.2.1. PUMPS

Pumps serve for the conveying of wastewater and can also be used as flow regulators. In UDS radial and screw pumps are usually applied. Axial pumps are less expensive but more sensitive to debris. Pumping stations in UDS are usually equipped with a number of constant or variable speed radial pumps to handle the wide range of flow rates. Possibilities of control are:
- fixed flow,
- low speed/high speed,
- continuous speed regulation,
- several pumps with different capacities.

If deep interceptors are used for in-line storage, the sump levels can vary considerably. In these cases the proper selection of the optimal operating points of the various pumps is important. Otherwise cavitation and excessive wear and tear can occur. If large flows have to be pumped, measures for transient suppression

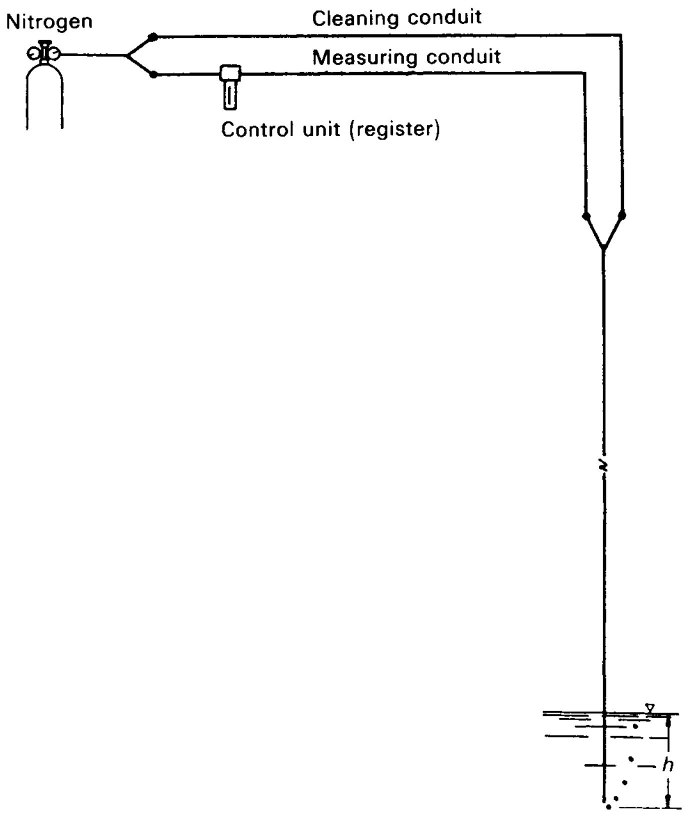


Fig. 46. Pneumatic bubble level sensor.

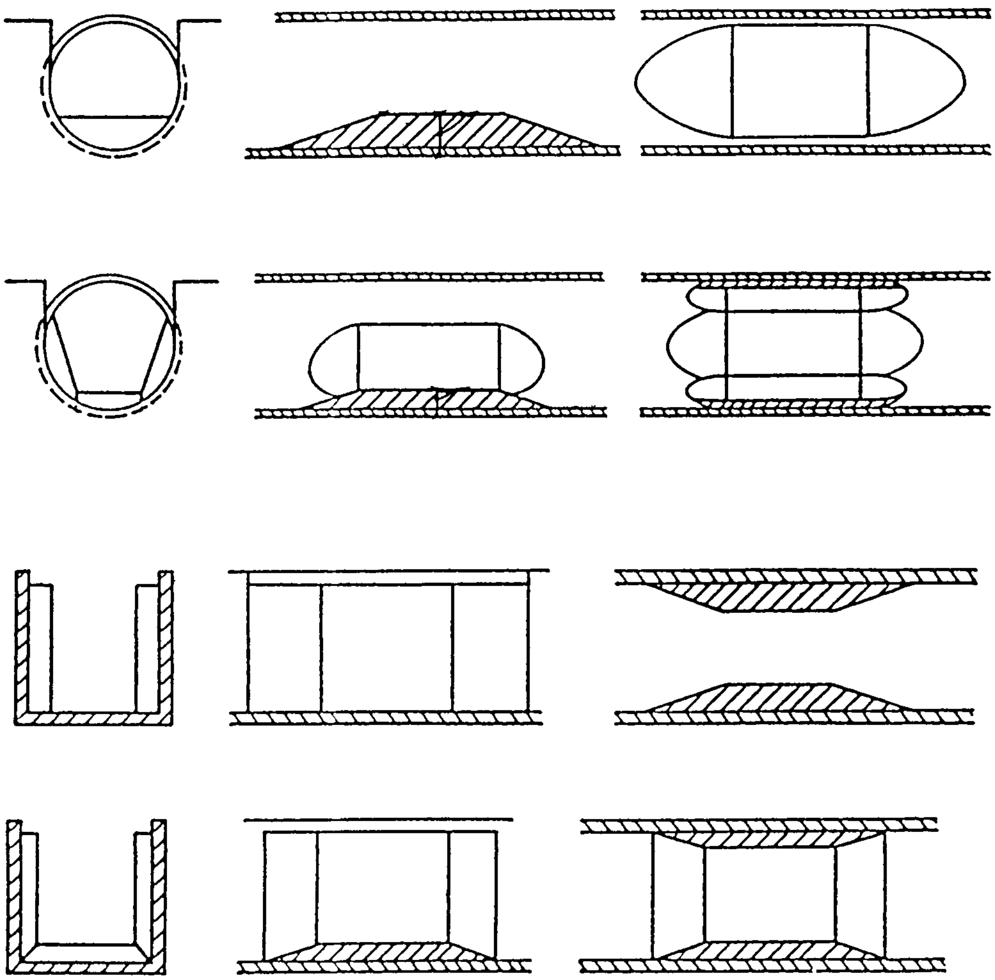


Fig. 47. Various shapes of flow measurement flumes (adapted from WPCF, 1986).

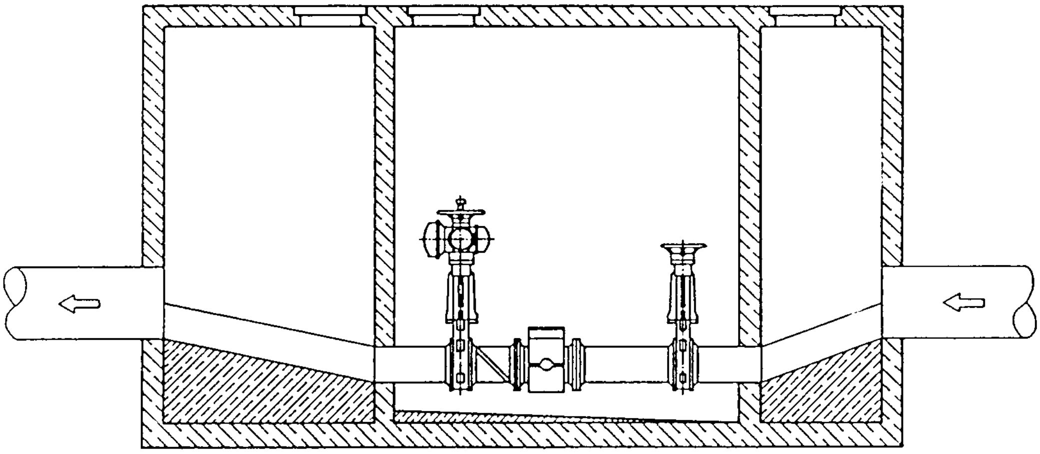


Fig. 48. Magnetic flow meter for pond outflow control (adapted from Fahrner, 1985).

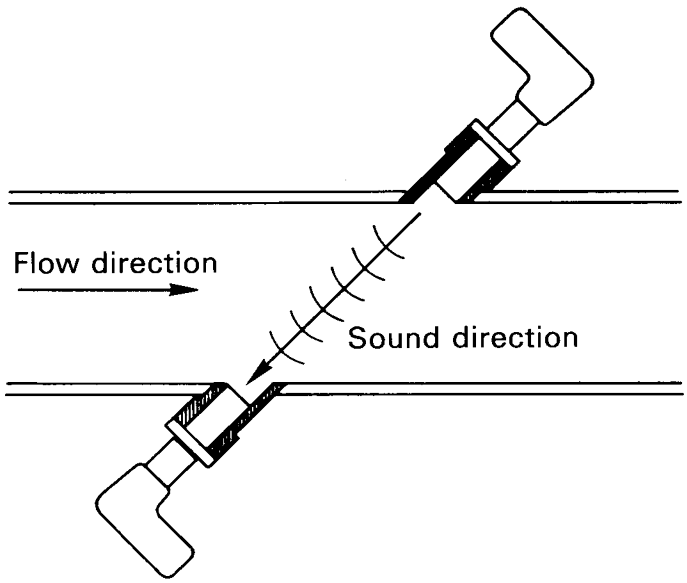


Fig. 49. Sonic flow meter (adapted from MAPCO, 1984).

have to be carefully designed to avoid upstream damage due to emergency shut off and subsequent surges and water hammer.

7.2.2 WEIRS

Moveable weirs (e.g. perpendicular, side-spill, leaping) can be used to increase the in-line storage in a sewer (Fig. 50). Combined sewer flows are usually regulated by fixed overflow weirs which typically operate passively. The dry weather flow and a certain amount of combined flow is directed to the treatment plant. Additional flows larger than the capacity of the pipe leading to the treatment plant escape untreated to the receiving water through the storm water outlet pipe. This might even happen in cases of minor rainfall when the capacity of sewers upstream of the regulator and the storm water overflow pipe are far from being fully utilized. In these cases it is desirable that the combined sewage should not discharge to the receiving waters unless a maximum allowable water level has been reached.

Several different techniques have been developed to improve this overflow problem. Three examples demonstrate how this can be achieved: The fixed weir can be replaced by either a pneumatically inflatable dam (Fig. 51), or a hydraulically operated gate (Fig. 52). Override controls are provided to protect the automated regulator and the wastewater collection system in the event of a computer or data transmission error. A high-level float switch installed downstream in the dry weather outlet (DWO) causes the DWO regulator to close if the DWO or interceptor level rises too high. Correspondingly, a float switch is located in the trunk sewer and opens the storm water outlet (SWO) regulator if the trunk level rises too high.

The air-regulated siphon (Fig. 53) represents another simple low-maintenance structure which, when used as a control element in storm overflows, offers advantages over fixed weirs. It allows the use of considerable additional sewer capacity. In this way the amount of discharged pollution due to the overflows can be reduced immediately.

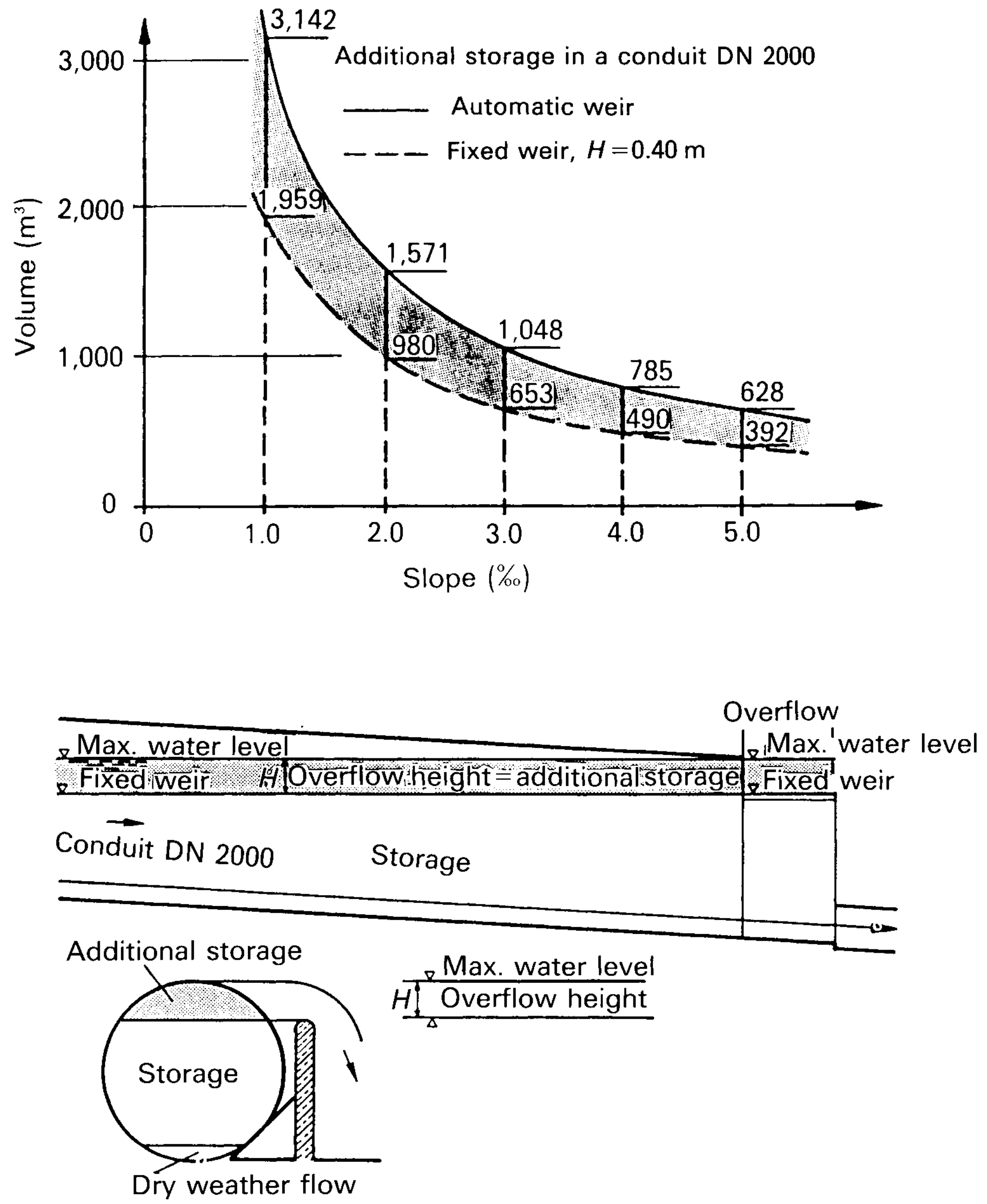


Fig. 50. Trunk storage capacity – comparison between automatic and fixed position side-spill weir (HST, 1987).

7.2.3 GATES

Gates (e.g. sluice, knife, radial, sliding) are plates made out of stainless steel, cast iron or hardwood to restrict flows. They typically move downward to the closed position. If this is not a safe position, gates require emergency by-passes such as high-crest sidespill weirs. Gates can be used to create in-line storage or to direct flows into parts of the UDS which still have void capacity (Fig. 54). Gates can be powered hydraulically or by electric motors. Pneumatic power is sometimes used as a back-up system for emergency operation. Gate movement should be fast enough to guarantee immediate control but slow enough to prevent surges. If used to create in-line storage their velocity should be reduced at close-to-crest water levels.

7.2.4 VALVES

Valves can also be used for flow restriction. Plug and butterfly valves feature rotating parts within circular pipe sections. They allow relatively precise flow control and are usually applied to control inlets into interceptors.

7.2.5 FIXED SET POINT REGULATORS

In the above-mentioned regulator systems, the set points are usually remotely adjustable. A great variety of regulators exist which do not feature variable set points. All of them have been designed to have 'maintenance free' flow regulation – a misconception as many examples prove. In the early 1970's the American Public Works Association recom-

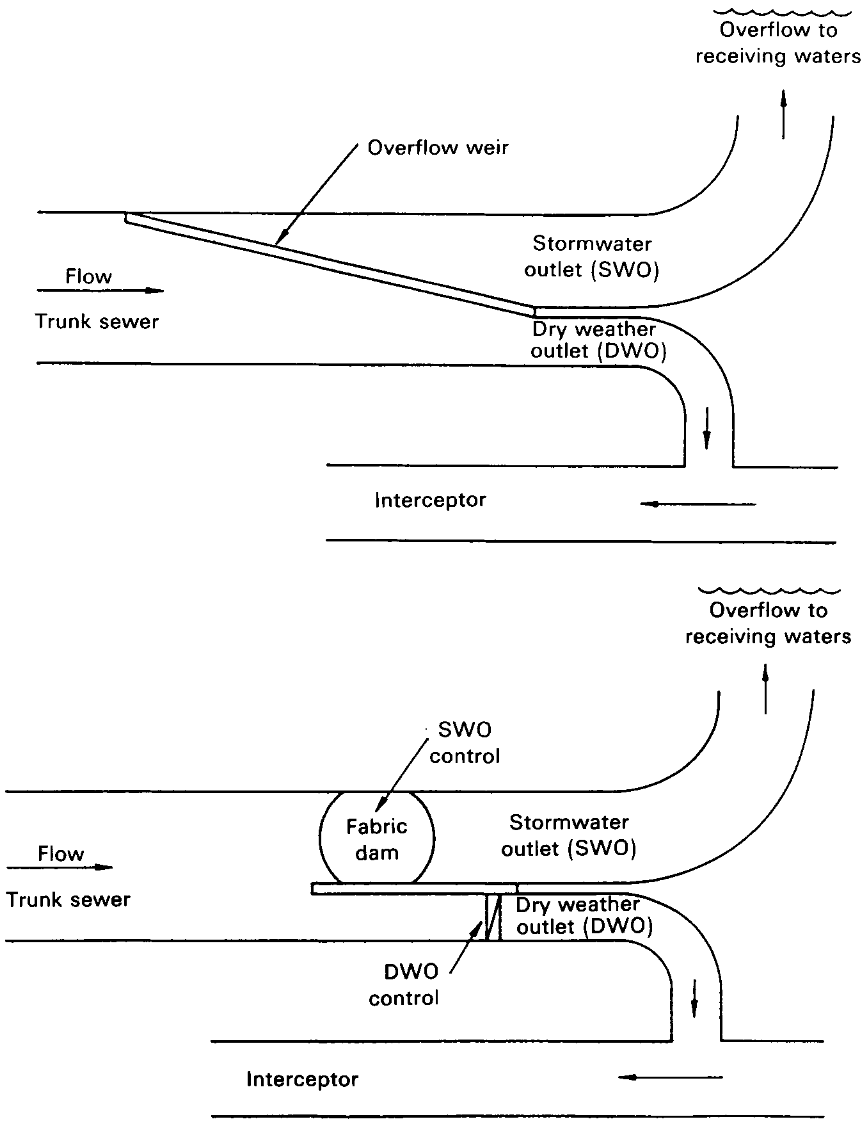


Fig. 51. Replacement of a side-spill weir by inflatable dam (adapted from Buczek and Chantrill, 1984).

mended the use of remote supervision for flow regulators to keep the regulators working properly (APWA, 1970b). Examples are, among others, vortex valves, float-regulated gates, float-regulated overflow weirs and air-regulated syphons.

7.3 Telemetry

7.3.1 ANALOG AND DIGITAL DATA TRANSMISSION

The monitoring and measuring instruments mentioned above have to transmit their data to the regulator, to the controlling system or to the information processing system.

If very short distances apply between the sensor/transducer, the controller and the regulator/motor, data transmission can be analog (e.g. pneumatic, hydraulic or electric). If the signals are immediately frequency modulated, transmission distances may be increased. Then the voltage or current transducer output is transformed into a frequency. This frequency can be used for further controlling purposes.

In a digital data transmission system, signals are converted to binary numbers. Thus, sequences of 1 and 0 rather than continuously varying signals are transmitted. In comparison with analog systems, digital telemetry systems have many advantages:

- digital data is suitable for direct data processing by digital computers,
- transmission reliability is higher,
- high transmission rates can be obtained,
- transmission over large distances is feasible.

If analog data is to be transmitted in digital form, it first has to be coded with an analog/digital (A/D) converter for input and, at the destination, to be decoded with a digital/analog (D/A) converter for producing the output signal. This is executed in the input/output unit (I/O).

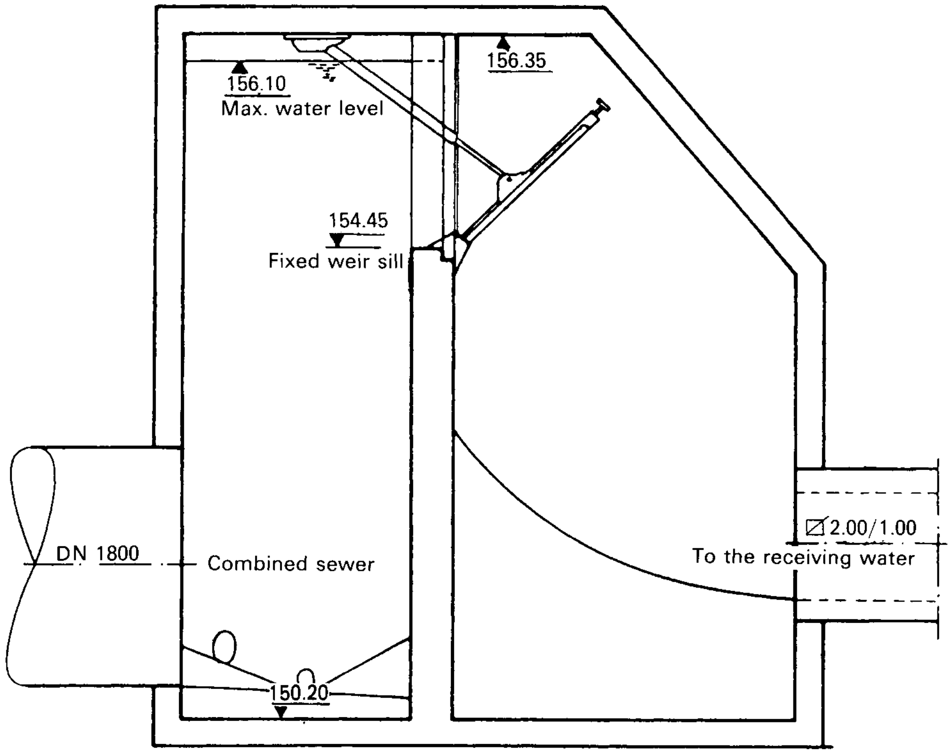


Fig. 52. Hydraulically operated overflow weir.

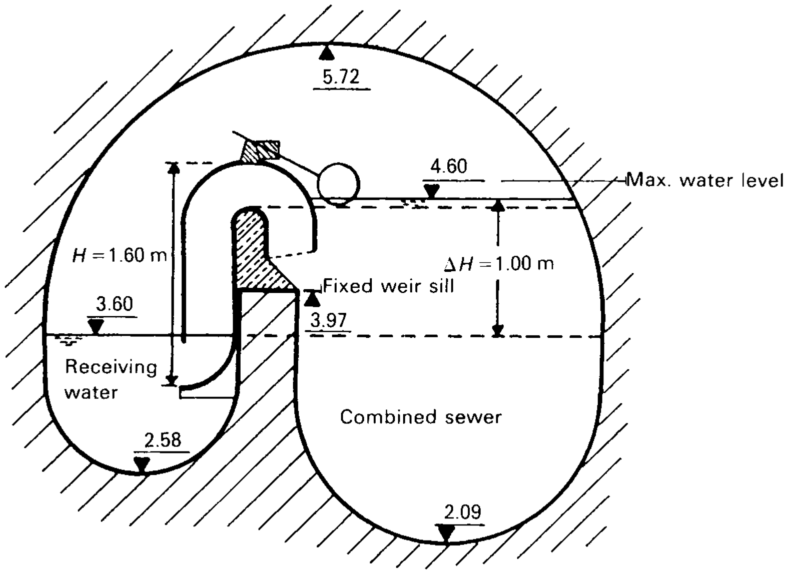


Fig. 53. Air-regulated siphon as overflow weir (HST, 1987).

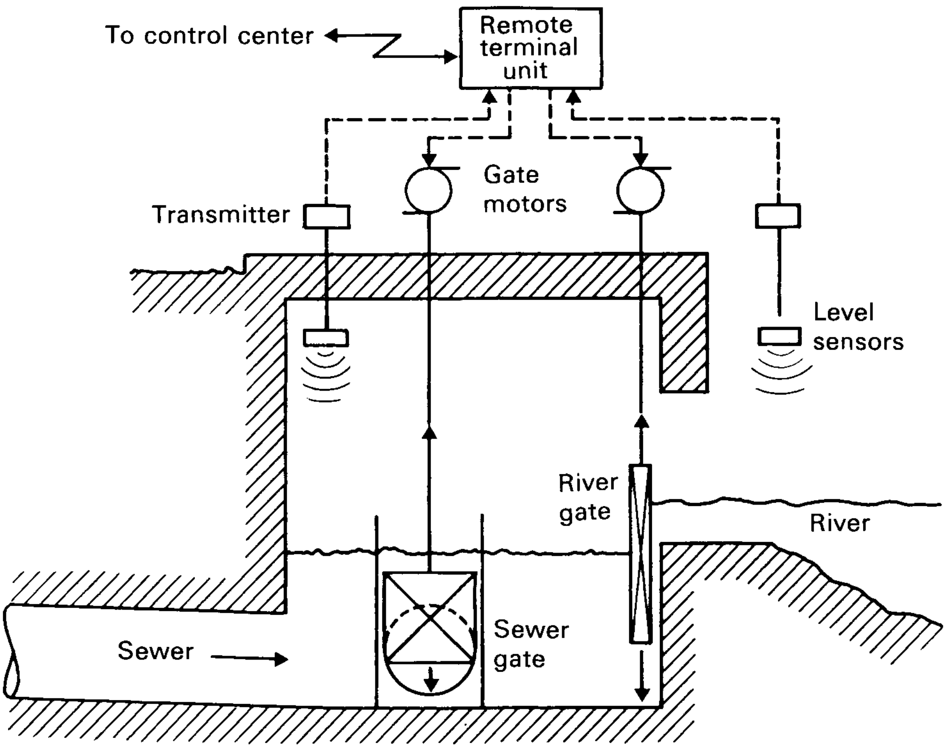


Fig. 54. Overflow regulator station (adapted from Brueck *et al.*, 1981).

7.3.2 INPUT/OUTPUT

In telemetry systems, data is collected in input/output units (I/O) before being transmitted for further data processing. In the opposite way, control signals have to be collected and passed on to the regulators by the I/O-unit.

Generally, these I/O-units are part of the telemetry unit and consist of various I/O-boards (Figs 55 and 56). In general the following types of signals can be distinguished:

- analog input (AI): analog measurement,
- analog output (AO): analog control, set point control,
- digital input (DI): digital measurement,
- digital output (DO): digital control, commands.

For every type of signal an I/O-board can be applied suitable for 4, 8, 16 or 32 signals of the same type. These signals can be further characterized as follows:

- AI:
  - twofold principle,
  - proportional measuring signal,
  - 4–20 mA/0–20 mA/0–5 V at sensor to be converted to binary numbers between 0 and 255 (2^8, 8-bit word),
  - uniformity (maintenance),
  - reliable,
- AO:
  - external set point alteration,
  - manual adjustment,
  - optimization,
- DI:
  - digital sensors (status 1 or 0),
  - active signalling,
  - voltage free contacts,
- DO:
  - separation between power current and weak current,
  - pulse control,
  - relay technique,
  - hold function in power current.

7.3.3 COMMUNICATION

In general a telemetry system consists of several remote telemetry units to collect the data, and a central unit receiving the data. It is connected to a computer system for further data processing. Central control actions, of course, are directed in the opposite way.

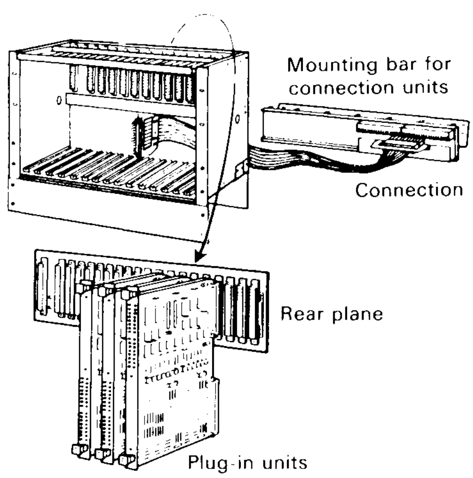


Fig. 55. I/O connection boards (ASEA, 1984).

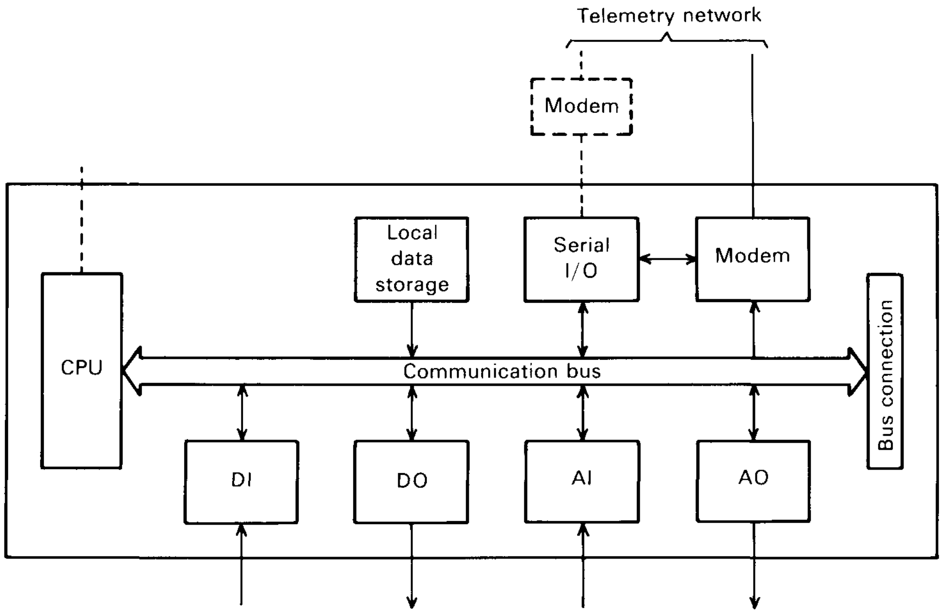


Fig. 56. I/O unit telemetry station.

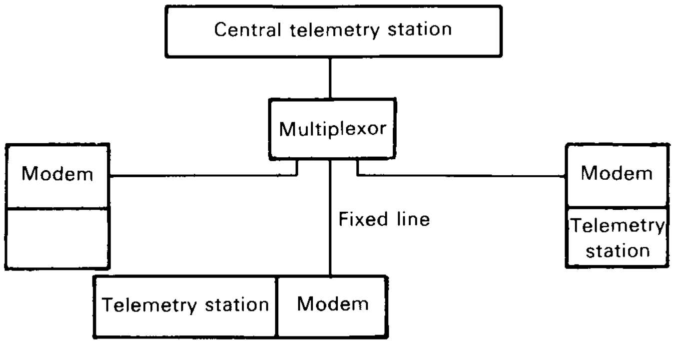


Fig. 57. Data communication with fixed lines.

For communication between the remote units and the central system, transmission can be facilitated by wire or wireless. However, in most European countries wireless transmission is restricted. Transmission by wire uses either privately owned, leased (fixed) or dialled public telephone lines (Figs 57, 58 and 59). Usually leased lines are used because of the following advantages:

– advantage can be taken of the service offered by the telephone company,

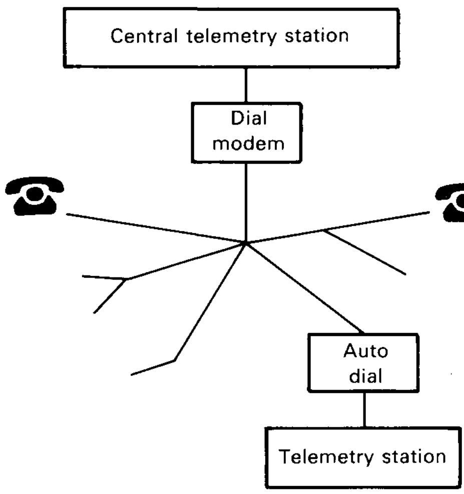


Fig. 58. Data communication with dialled telephone lines.

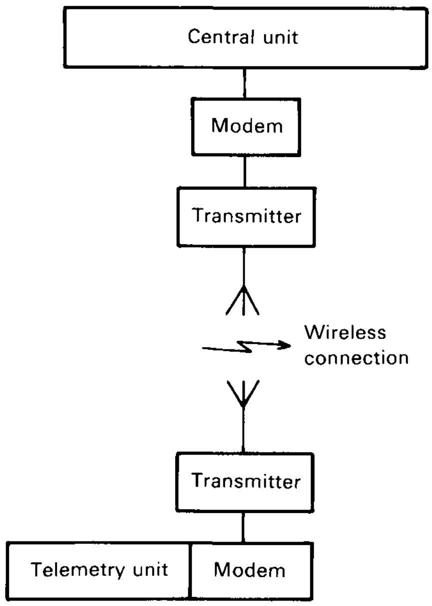


Fig. 59. Wireless communication.

- transmission is possible at high rates,
- transmission is reliable and always available,
- transmission reliability is controllable, error checking can be applied to a high level,
- continuous sampling of analog signals is possible,
- relatively large amounts of data can be transmitted from one telemetry unit,
- it is especially appropriate for exchange of analog I/O.

Of course, these advantages can also be taken into account for privately owned lines. In general, private or leased lines are most effective for short distances. Dialled lines are preferred when data transmission over long distances (e.g. >10–20 km) is required and transmission is not required at all times.

Before sending the data by wire, the telemetry unit has to modulate the digital signals into a certain frequency (tone). At the other end, the central unit has to demodulate the frequency back into a digital signal. Hence, for sending and receiving, modems (modulator-demodulator) have to be applied. Modulation techniques often used are amplitude modulation (AM), frequency shift keying modulation (FSK) and phase shift keying modulation (PSK).

Several logic channels can be transmitted within one physical channel if multiplexing is applied. With frequency multiplexing a frequency band, and with time multiplexing a time slot, is assigned to each logical channel. Communication is possible one way only (simplex), one way at a time (half duplex) or two way at the same time (full duplex).

Required capacities of transmission channels depend on the number of data points, the scanning frequency, the amount of information per scan and data point, and the error detection technique that is applied. A standard for data transmission via public telephone lines is 1200–2400 bits/sec (bps) for dialled lines and 4800–9600 bits/sec for leased lines.

Other techniques, such as fibre optics, provide transmission at very high rates, but are not yet commonly available for RTC.

7.3.4 NETWORKING

As already mentioned in the preceding chapter, telemetry systems are generally implemented as a network of remote units connected to a central data acquisition system (Fig. 60). The central system can be equipped with modems, a telephone exchange unit and a computer to provide functions for control and operation of the real-time control system. In relation to the networking aspects the following is relevant:

- the topology of telemetry networks is generally star shaped,
- local storage of actual data may be necessary,
- the scanning of data of a remote telemetry station should always provide a consistent block of information to the central unit,
- telemetry stations communicating over dialled lines will need an autodialling modem to start communication with the central unit automatically,
- in fixed line networks the central unit generally scans (polls) the remote units for data changes (multidrop polling).

In networks the communication lines may be malfunctioning. Both the central unit and the remote units should be able to detect severe communication errors. In such cases the local devices are no longer under central control. A watchdog system in the local units can detect this situation and put the element of the UDS under local (automatic) operation, i.e. into a pre-defined safe state with respect to the UDS. The part of the control system that remains in function has to deal with this situation.

From experience it appears that dealing with partial system failures takes at least 50% of the total software effort in centrally controlled urban drainage systems.

7.4 Controllers and process computers

7.4.1 CONVENTIONAL ANALOG CONTROLLERS

Mechanical or pneumatic controllers are still often applied. However, these types of analog controllers cannot be remotely modified. Time varying set point adjustment is not feasible in RTCS equipped with mechanical or pneumatic controllers. With the development of microprocessors many analog controllers could be replaced by microprocessor-based PID-controllers, programmable logic controllers (PLC) or computers. This also allows for a lot more flexibility, operator convenience and real time integration of control functions in UDS.

7.4.2 PROGRAMMABLE LOGIC CONTROLLERS

Developments in very large-scale integration of circuits (VLSI) have been the immediate cause of the appearance of microprocessors and their numerous applications (e.g. in single board computers). Microprocessor based systems are programmable and, therefore, very well suited for all kinds of controlling functions in RTC of UDS. For instance they are applied in local controlling devices such as PID controllers, field panels and telemetry units. Their application is still growing because of the steadily decreasing price/performance ratio of these systems.

One of the devices with the most potential and wide range of possible applications for local control is the programmable logic controller (PLC). Since 1974, PLC's have been

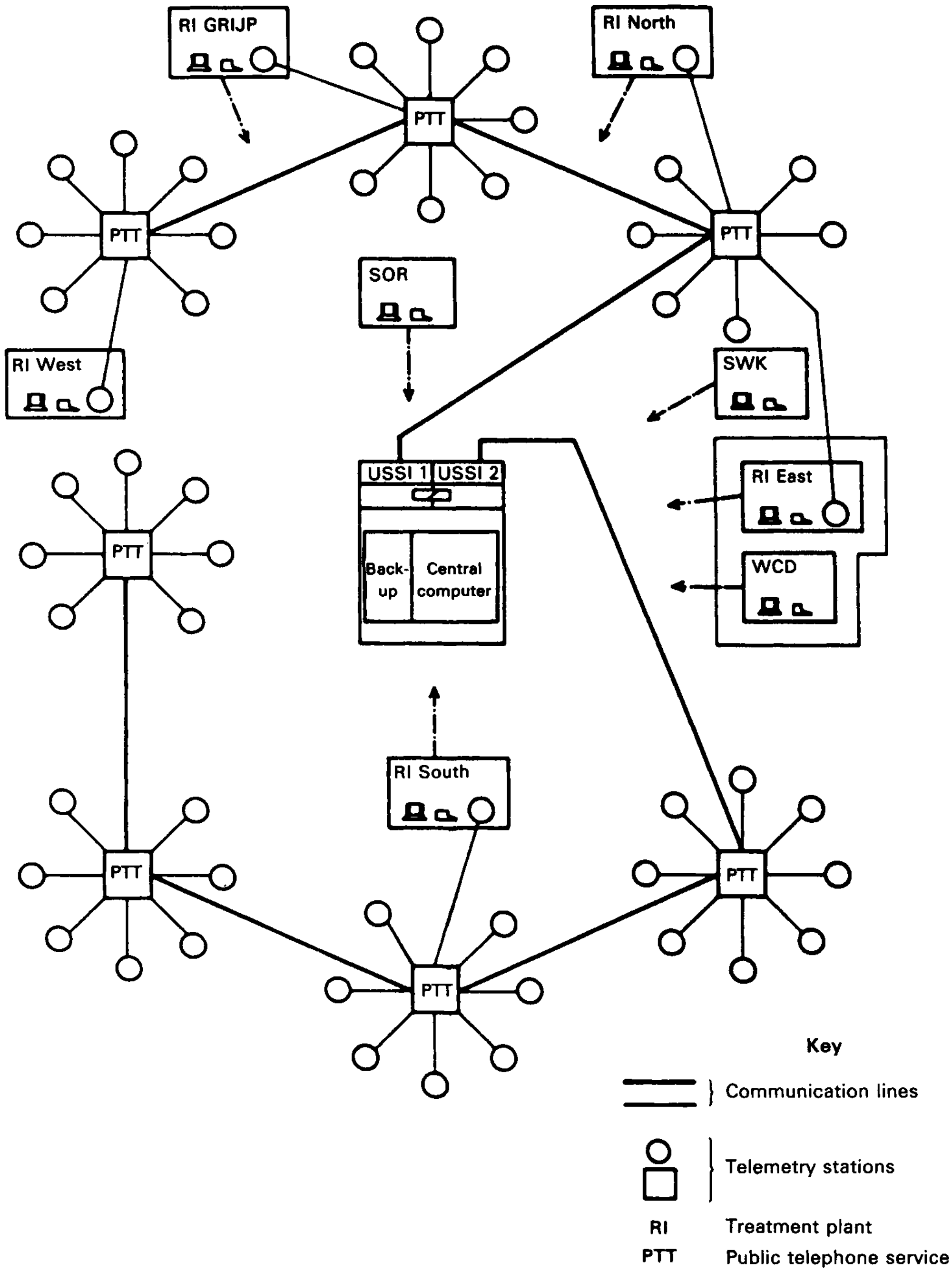


Fig. 60. Telemetry network of the Amsterdam RTC system (adapted from Schuffelen, 1985).

applied to replace the conventional relay techniques. They allow design of logical electrical circuits in the form of software. Essential for the PLC is that they can be programmed in the same way as the conventional set-up of relay schemes.

The PLC program is usually in non-volatile erasable programmable read only (EPROM) memory. It is set up with a special instruction set for the PLC. In the PLC, the program is run in a scan cycle usually between 1 and 30 ms. On the basis of the scanned input signals (I/O boards), the process is then controlled (Figs 61 and 62). The possible functions for PLCs in RTC of UDS are:

- all local control functions as PID, three point control etc.,
- time delayed switching,
- pulse counting,
- signalling + alarming and communications to central control level,
- remote I/O,
- remote set point adjustment, e.g. from central level,
- local data processing.

The advantages of PLCs are:

- the functioning of the program can be tested and simulated before putting it into operation,
- simple programming with many standard control functions,
- flexibility/modularity,
- reliability,
- ease of maintenance,
- only little space required,
- reduction of cabling.

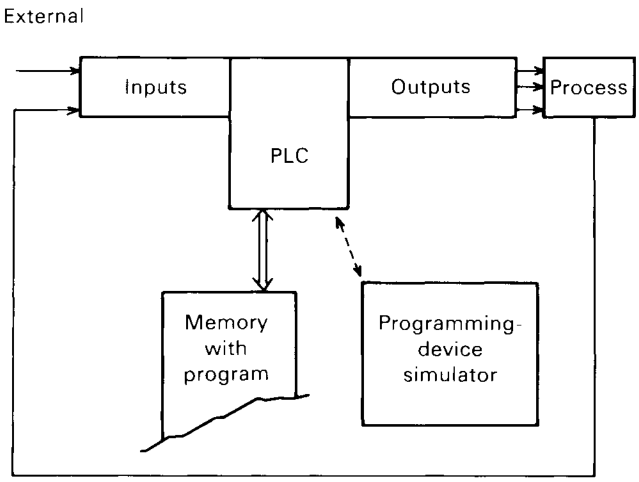


Fig. 61. Programmable logic controller (PLC).

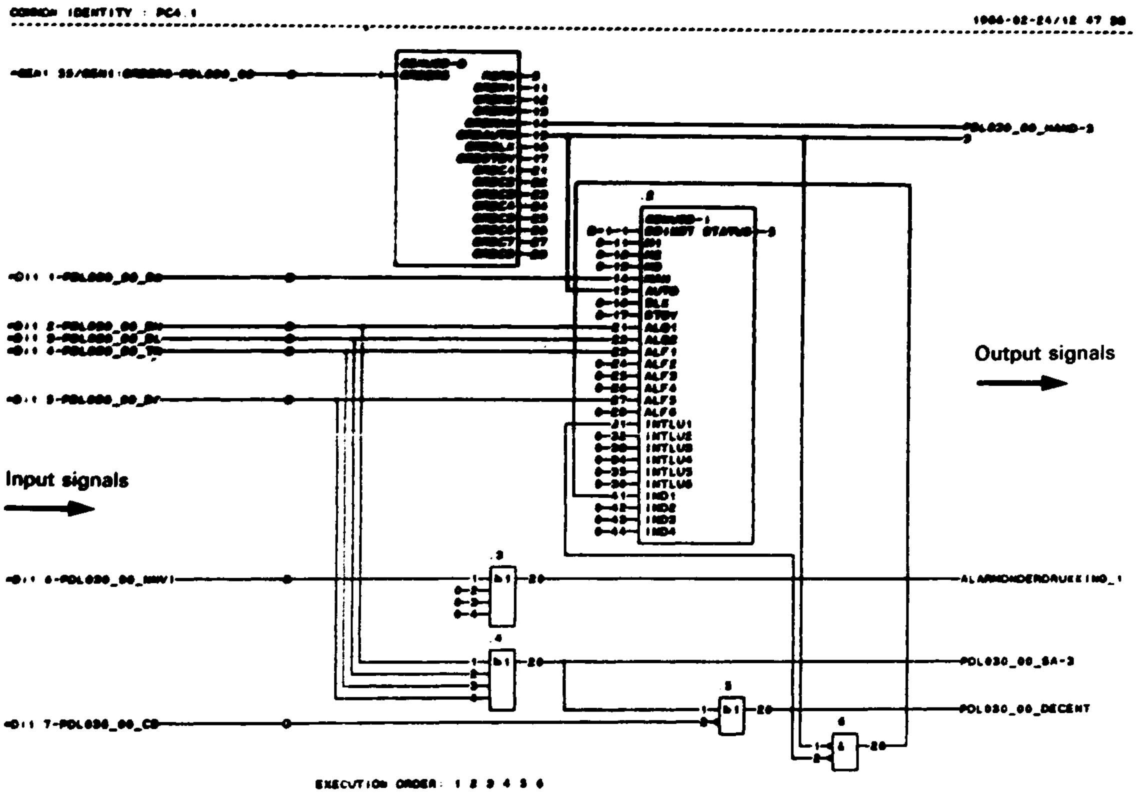


Fig. 62. Example of PLC program (ASEA, 1984).

The disadvantages are:

- additional devices are necessary for programming,
- no possibility of storage of historical data,
- no direct check on the functioning of the process,
- no direct operating facilities.

Nowadays, PLCs are available which meet the above constraints. A PLC can be provided with a large memory (2–4 Mbyte RAM), advanced programming tools and possibilities (e.g. programming by microcomputers), high level language programming facilities (e.g. BASIC, PASCAL, FORTRAN, C), graphic documentation and telemetry functions. In the same way, the telemetry stations discussed in Chapter 7.3 have become far more flexible ('intelligent') and can be equipped with control loops for simple pump or valve control.

7.4.3 PROCESS COMPUTERS

There are only slight differences between programmable logic controllers and central process computers. In distributed real-time control systems their tasks are somewhat interchangeable but in general the PLCs are used for local control and pre-processing, while the central process computers are applied for global control and further data processing.

Process computers are characterized by the fact that they are equipped with a special real-

time and multi-tasking operating system. In that way process computers may differ from conventional mini- and micro-computers. The most important functions of process computers in RTC of UDS are:
- central system for the acquisition, storage, processing and presentation of data of the RTCS,
- provision of remote operation (manual) facilities for supervisory control of the UDS,
- automatic overall control functions for the UDS.

Advantages of process computers are:
- wide variation of available systems,
- flexibility,
- modularity,
- large processing power to execute complex control strategies.

Disadvantages are:
- programming and maintenance requires specialized personnel,
- vulnerability.

The software for process computers is generally written in a high level and standardized programming language. The software for the overall control of the UDS, therefore, is transferrable to other computer systems. An important aspect of the functioning of process computers is the software set-up (Fig. 63).

Process computers are multi-tasking systems, so several programs can be active at the same time. The central part of the software is formed by the database or process base. This database always contains the most recent information of the RTCS. The reliability, integrity and consistency of this base requires much attention. The database serves as the key resource of information for further automatic or supervisory (manual) control of the UDS.

For the operation and presentation of information, use is made of especially developed display systems (Fig. 64) which allow for advanced graphical display presentations (video commanding systems). Furthermore, the process computer is provided with various peripherals such as I/O-devices, terminal controllers, printers, plotters, disk storage, etc. (Fig. 69).

7.5 Summary, discussion and conclusions

In a RTCS a large variety of hardware elements are used for regulating, measuring or signalling purposes. Sensors applicable for RTC in UDS include rain gauges (e.g. drop

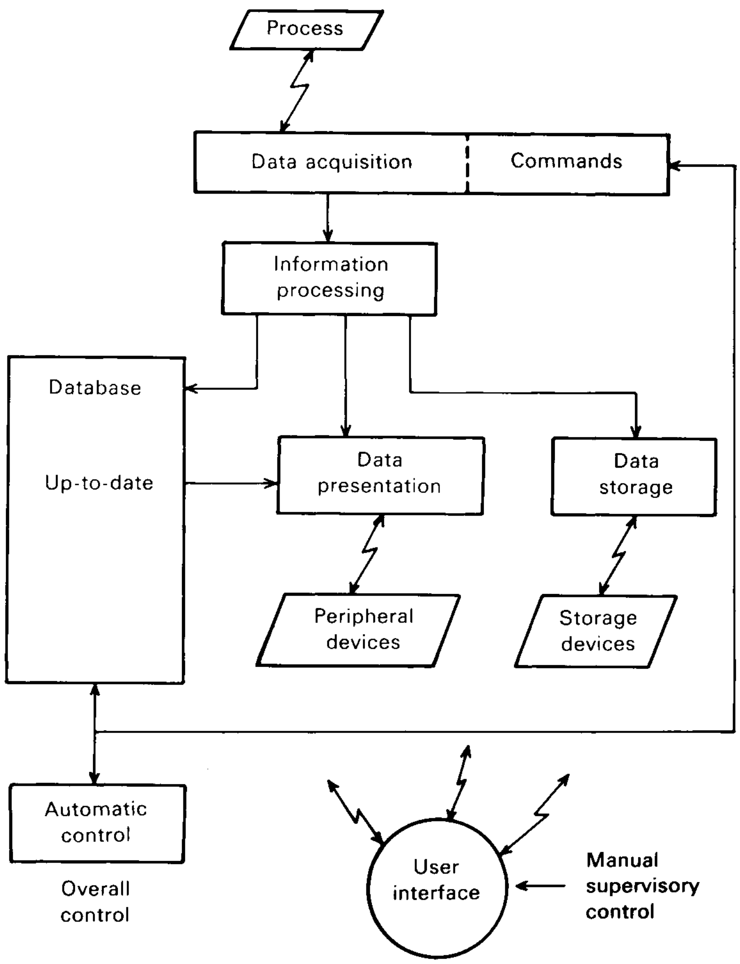


Fig. 63. Software set-up for process computers.

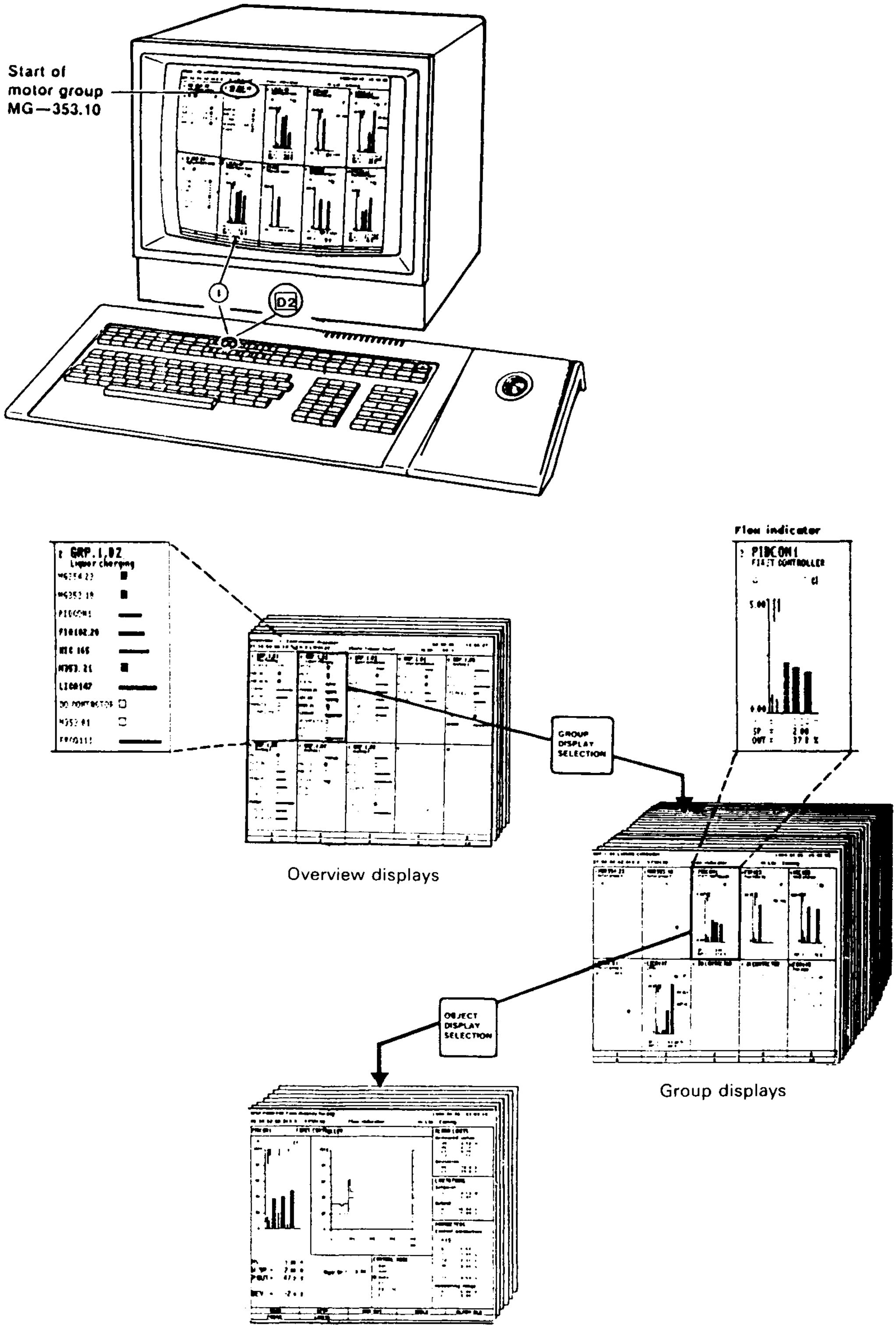


Fig. 64. Video command system (ASEA, 1984).

counter, tipping bucket), weather radar, water level gauges (e.g. pressure probe, bubbler, sonic sensor), flow gauges (e.g. level-flow transformation, electromagnetic, ultrasound, flumes). Sensors for pollutant parameters are not yet available for routine application in RTC of UDS. Very often limit switches (e.g. float, conductive, capacitive) are applied to support simple on/off control.

Regulators require careful design to withstand the hostile environment in UDS. Applicable are pumps (e.g. radial, screw), weirs (e.g. perpendicular, side-spill, leaping), gates (e.g. sluice, knife, radial, sliding), valves (e.g. butterfly, plug), and fixed set point regulators. The latter do not require an external energy supply but have only limited flexibility with respect to global control systems since they do not allow the modification of set points.

The measured values have to be transmitted to a controlling unit and from there back to the regulators. In practice, digital communication between these units gives the best performance and enables the execution of more advanced control strategies.

UDS may cover a wide geographical area and hence measurement, signalling and local control can be very distributed. A telemetry network provides for the necessary communication facilities. Such a network collects all the data of the status of the RTCS to a central point. From there, actions can be carried out manually or automatically to execute supervisory or automatic control strategies.

For local control, programmable devices are preferred such as programmable logic controllers (PLC). They can be integrated in the telemetry network. The central unit generally comprises a telephone exchange unit and a subsequent process computer. Also the network often makes use of the public telephone system, which is used to couple central and local telemetry stations. Communication takes place by adapting the digital signals to the carrier medium (modulation) and is controlled by complex error checking protocols and data handling mechanisms.

The process computer offers the facilities for advanced operation of the UDS. Also, complex control strategies can be developed in high-level software for overall control functions. The continuing developments in computer hardware and software and the decreasing price/performance ratio will ensure that in future the possibilities for overall control will be enlarged to a great extent.

8. Applications

THE first comprehensive approaches to RTC in UDS were initiated in the **United States** at the end of the 1960s. In the 1970s a number of demonstration projects were implemented and are mostly still in operation. An overview on American RTCS is given in Section 8.2.

It is more difficult to obtain an overview on RTC applications in Europe because of the many different countries with their respective administrative regulations.

For example, some **German** states enforce specific CSO regulations. These resulted in the construction of literally thousands of small detention tanks to catch the first flush of pollutants in CSS. Some 20% are equipped with controllable regulators. Quite a few employ some form of regional control, mainly to avoid downstream CSO caused by upstream tank releases. As for large supervisory real-time control systems, examples can be found in cities such as Bremen, Hamburg, and Munich.

Large parts of **The Netherlands** are below sea level. There, virtually every drop of water in UDS has to be pumped, mostly from CSS. Hence, in a strict sense, all drainage systems in The Netherlands are under RTC. Integrated systems, of course, are not so frequent, e.g. Rotterdam, Wervershoof, Utrecht, and Eindhoven.

The county of Seine-St-Denis, close to Paris, has operated a large real-time control system for more than a decade. Other existing or planned real-time control systems in **France** include the counties of Hauts-de-Seine, Val-de-Marne, and the cities of Nancy and Bordeaux.

After the re-organization of water resources management and administration in **England**, the number of integrated real-time control systems is steadily increasing. Solely dedicated to wastewater control, for example, are the systems in Newcastle-upon-Tyne, Birmingham/Wolverhampton, and Grimsby/Cleethorpes.

8.1 History of real-time control in urban drainage systems

In the 1960s the steel and oil industries started to implement prototypes of automatic process control using the first process control computers (IBM 1800 or DEC PDP). Since then, many plants have been automated.

Also at this time, prototypes of sewage treatment plant computer control systems were built (e.g. Brouzes in Achère, France). At the same time the first urban drainage system real-time control system was implemented in Minneapolis–St. Paul (Anderson, 1970).

These prototypes were aiming too high compared to the general state of technology of the wastewater industry: energy savings or better environmental efficiency were the main benefits of these prototypes. Energy savings did not appear to be very important before the 1974 energy crisis, and environmental benefits were not assessed properly due to the transient nature of pollution events and to the lack of experimental evidence of their impacts. The RTCS were implemented as a competitive solution against sewer separation or construction of large interceptors. Most sewer managers had a civil engineering background and, hence, were more at ease with large construction works than with daily evaluation of pollution, assessing misuse of the drainage network and controlling flow propagations and biological reactions. In the seventies, a few American cities (Seattle WA, Lima OH, Cleveland OH) implemented RTCS to reduce the number of combined sewer overflows. This was primarily done to delay large investment for sewer separation and to receive additional funds from the US Environmental Protection Agency.

Other North American cities (e.g. Montreal, Quebec, or San Francisco CA), and some European cities (e.g. Hamburg and Bremen in Germany) started feasibility studies on RTC. Their main objectives were to show the benefits of reducing the frequency of overflows. Only a few of these cities implemented such a system. Hydraulic problems (e.g. water hammer), flooding and increased solids settling, appeared to cause more problems than what could be gained in terms of environmental benefits.

At the onset of the 1980s hardly any further progress in RTC applications occurred. A new chapter started with the technology revolution of the microprocessor: remote pumping stations could be controlled with these inexpensive new local intelligence devices. Within a relatively short time a large number of these devices were implemented resulting in decreased pump wear or lower energy costs.

This equipment was the first 'RTC equipment' to be accepted by the sewer operation departments. Those were handy devices, not difficult to implement and did not threaten the routine work of sewer operation.

In the meantime, numerous studies had proved that the sewer network is the weak link in the struggle for less pollution. False connections, overflows in treatment plants due to infiltration and inflow, shock loads, and toxic pollutants dispersed by street runoff, were reported. Moreover, large cities experienced extensive floodings which were concealed as so-called 'more than decennial events'.

The routine work of sewer operation started to be questioned by numerous scientists. Awareness rose in some cities. Managers understood how little information was really available to them in order to run their sewer networks properly. Data logging was used to gather this information. Yet, this information was usually fairly unreliable: due to a lack of interest data loggers were mostly poorly maintained so that they did not work during critical events.

Much better data could be collected with centralized data collection systems which used remote data transmission (data acquisition systems, management information systems). For most sewer managers RTC still means data acquisition and remote manual control of pumping stations.

It is only recently that some cities have started to move into comprehensive real-time sewer management which is going to change daily operation more drastically than ever experienced before. Therefore, a conclusion would be that, in most existing UDS, RTC has not yet started and that up to now the history of RTC in UDS could be called a 'pre-history'.

8.2 North American real-time control systems

This section is based on a 1984/85 survey of **United States** and **Canadian** RTCS using a questionnaire and personal communications (Schilling, 1985a). Table 2 shows how differently some agencies recognize their past and present urban runoff problems with respect to CSS, mostly in ranked sequence.

Table 2 **Problems with combined sewer systems**

	wet weather overflow	dry weather overflow	over-designed	corrosion	detention basin not effective	infiltration/inflow	septic conditions	structural breakdown	sediments	flooding
Akron, OH	3					2			1	
Albany, NY	1					2			3	1
Boston, MA		1				2		4	3	6
Chicago, IL	x									x
Cleveland, OH	1	2								3
Detroit, MI	1	2	9	8		4	6	7	3	5
Edmonton, Alta.	2	4				3				1
Evansville, IN	7	2				6	5	3	4	1
Grand Rapids, MI	1				4	3				2
Hamilton, Ont.	3	2	1	1		1	1	1	1	3
Indianapolis, IN		1				4		3		2
Lima, OH	2					3			4	1
Milwaukee, WI	1	2								
Minneapolis-St. Paul, MN	1	2				4				3
Montreal, Que.	2	1				4				3
Omaha, NE	2	1						3	4	5
Ottawa, Ont.	x									
Peoria, IL	x									
Philadelphia, PA		x				x		x	x	x
Providence, RI	1	5		9	7	4	8	2	3	6
Rochester, NY	2							3	4	1
San Francisco, CA	x									
Seattle, WA	2	1								3
St.Louis, MO	2	1				2		2	2	
Toledo, OH		3				2			4	1
Toronto, Ont.	1									2
Vancouver, B.C.	1					x		x		x
Washington, DC	1	2								3

Infiltration/inflow and dry weather diversions are mentioned quite often, thus indicating basic upgrading and treatment capacity needs.

In Table 3 the currently pursued approaches to solve these problems are listed. According to this rather non-representative survey, separation, additional storage, and RTC of the existing systems, are the more frequently applied approaches.

Table 4 gives a comprehensive review of some characteristic numbers of existing real-time control systems some of which are described below. Surprisingly, these systems have almost nothing in common. Successful real-time control systems exist in both large and small catchments. Available storage, as well as population served, differ by magnitudes. Apparently RTC is feasible and effective for a wide variety of combined sewer systems.

8.3 German real-time control systems

At present, Germany seems to have most RTCS. The reason is mainly that CSO regulations require the construction of detention ponds at each overflow site. Therefore, a vast number of UDS exist with tens of ponds each. If these ponds are only controlled by an orifice their performance is not satisfactory (e.g. one pond overflows while another one is still empty). In larger drainage systems the sheer complexity of the networks requires some form of remote supervision which is often gradually extended to RTC.

One of the first RTCS in Germany has been installed in the City of **Bremen**. Two large storage tanks, additional in-line storage, five pumping stations and overflow gates are under supervisory RTC. The system has been in operation since the early 1980s and is presently under review for improvement and extension.

The City of **Hamburg** operates one of the oldest 'modern' sewer systems in the world (construction began in the 1850s). Serious sedimentation, corrosion and overflow problems require a spectrum of actions of which the installation of a RTCS is only one. Ultimately five regional control centres will control a number of detention ponds, gates, pumping stations, and inverted siphons in the system.

The City of **Munich** is greatly expanding the storage capacity in its combined sewer system. Before the turn of the century some 500,000m^3 of additional pond storage will be available, mostly as underground concrete tanks. For the development of the control strategy of these ponds, the existing remote monitoring system is going to be expanded to 20 rain gauges, 66 water level gauges and 4 continuous water quality monitoring stations along the receiving Isar River.

The City of **Nürnberg** is presently constructing an oversized interceptor sewer. The storage volume of 50,000m^3 will be controlled by seven large sluice gates with by-passes. It is planned to allow for both simple local control as well as advanced systems control strategies.

The **Ruhrverband**, a large sanitary district in the heavily industrialized Ruhr area, is in charge of 150 detention ponds (another 350 planned) many of which are controlled by fixed set point regulators. In the networks of **Brilon**, **Neheim**, and **Ense** RTCS are either already installed or planned.

A number of small town systems (**Herrenberg**, **Münsingen**, etc.) have some semi-automatic RTCS for their stormwater ponds. Whereas the activation of the ponds is automated, the emptying commands are manually given from the treatment plant personnel.

8.4 Dutch real-time control systems

The Dutch situation is characterized by a very flat landscape, a high groundwater level and large parts of the country below sea level. For urban drainage mostly combined sewer systems are used. Nearly all the water in UDS has to be pumped. Storage is carried out in the sewer system itself by means of the sewer volume. The construction of storage tanks is not often undertaken because of the very high construction cost. Therefore, in most cases, the only controllable element of the drainage system is the pump itself and, sometimes, a (regulating) valve.

In the **Netherlands**, the provinces are responsible for the control of water pollution. They often delegate this task to a number of water authorities. These water authorities are responsible for the treatment of (urban) wastewater, e.g. by means of the construction of sewage treatment systems and by the formulation of requirements and standards concerning the discharge of combined sewer overflows into the surface waters. The municipalities are responsible for the construction, maintenance and management of the urban drainage systems. Therefore, municipalities like to apply RTC because it reduces the necessary amount of sewer in-line storage, while the water authorities intend to use the existing storage as much as possible to alleviate flows to the treatment plant.

In both cases the ultimate aim is to reduce construction cost of both sewer in-line storage and treatment plant. Other aspects such as energy saving, real-time water quality management, or optimal functioning of the complete wastewater system, are considered profitable side effects.

One of the first RTCS in the Netherlands has been installed by the water authority of the River Dommel at the treatment plant of **Eindhoven**. The system controls a large gravity flow main sewer to which many small villages are connected. The storage, as well as

Table 3 Application of combined sewer overflow abatement techniques

	sewer grouting	better maintenance	real-time control	surface retention	source controls	combined sewer overflow treatment	regular flushing programs	new detention basins	new collector mains with fixed regulators	new collector mains	separation
Akron, OH		x									
Albany, NY								x	x	x	x
Boston, MA		x			x	x		x		x	x
Chicago, IL			x							x	
Cleveland, OH			x								
Detroit, MI			x								
Edmonton, Alta.								x	x	x	
Evansville, IN			x								
Grand Rapids, MI			x					x	x		
Hamilton, Ont.						(x)				(x)	
Indianapolis, IN	x				x		x				
Lima, OH			x								
Milwaukee, WI			x							x	x
Minneapolis-St. Paul, MN			x								x
Montreal, Que.			x							x	x
Omaha, NE			x						x	x	x
Ottawa, Ont.						x			x		x
Philadelphia, PA		x	x				x			x	
Rochester, NY			x			x			x	x	
San Francisco, CA			x			x				x	
Seattle, WA			x								
St.Louis, MO			(x)								
Toledo, OH				x	x	x		x			x
Toronto, Ont.			x						x		x
Vancouver, B.C.			(x)					(x)			
Washington, DC			x			x				x	

Table 4 Characteristic data of RTC systems

	Lima	Seattle	Detroit	San Francisco	Cleveland	Chicago	Minneapolis–St. Paul	Philadelphia	Montreal
Total area (km^2)		873	1670	97.2	430	2260	4120	258	365
Combined sewer area	15	52.8	636	96.2	184	972	77.3	170	273
Area slope	Flat	Mod.	Flat	Steep	Mod.	Flat	Mod.	Mod.	Mod.
Population (Mill.)	0.047		3.2		1.3	5.25	1.7	2.25	1.9
Overflow structures	5	81	110	39	>500	645	120	184	125
Storage volume ($1000m^3$)		34	120.4	530	235	11230			
Storage volume (m^3/ha)	22.7	22.7	8.3	69.5		115.5			7
Rainfall monitors	0	11	41	27	25		9	13	10
Water level monitors	13	70	247	<120	100	77	44	7	50
Monitored overflow locations	5	37	110	0		211	18	4	14
Out-stations	9	36			69		38		
Data points	300	800	475		1500	1900	139		>444
RAM storage (kByte)	2x52	45	24	16	2x>128		24	16	2x?
Controlled regulators (without pumping stations)	8	16	10	0	34	64	6	3	14
Pumping stations	1	21	17	2		3	0		1

the capacity of the main, is controlled by three regulating stations equipped with regulating valves. The global control is carried out in the central control room manually by means of set point adjustments. Also fully automatic overall control has been implemented, with varying results. The system has been in operation since 1975.

In the region of West-Friesland, in the province of North-Holland, a fully automatic global control system has been functioning with very good results since 1983. The system controls 28 sewage pumping stations, using spatial distribution of rainfall in the area of the regional treatment plant situated at **Wervershoof**. The system is further described in Section 8.8.6.

In the City of **Amsterdam**, a large management information system for more than 200 sewage-pumping stations is in operation. The pump data is monitored in a central control room and used for maintenance or operational purposes. The pumps can be manually controlled from the control room. The pumping stations are provided with telemetry equipment, which can be adapted with software for local pump control.

In the City of **Rotterdam**, the sewer system is also used for drainage of the groundwater. In former days the water was pumped to the surface water. Nowadays the water is pumped to the treatment plants with a hydraulic capacity far below the total pumping capacity of the sewage-pumping stations. The municipality of Rotterdam installed an advanced remote-control system for several dozens of pumping stations. The pumping stations are equipped with PLC-controlled and speed regulated pumps, maintaining a certain receiving water level under local control mode. This water level can be manually adjusted from the central control room. Automatic integrated control of the storage capacity is planned for the future.

Many cities in the Netherlands have planned to install systems with central monitoring functions and remote control of pumping stations. The City of **Utrecht** will complete a fully automatic system by the end of 1987, also optimizing the use of the storage in the sewer system.

The City of **Schiedam** is just about to start the implementation of a RTCS for optimal water management under extreme rainfall conditions. The city is situated almost completely below sea level, so there is no possibility of gravity overflow out of the sewer system. Due to the specific Dutch situation, it is evident that real-time control concepts developed for urban drainage systems are also applicable to integrated real-time water management of the surface water.

8.5 French real-time control systems

At present, French RTCS are small in number but their technology is more advanced. Some are fully operational and their implementation changed day-to-day management and operation drastically. One of the reasons might be that current French regulations call explicitly for the use of new technology.

Many French UDS include telemetry systems which allow remote supervision of retention ponds, pumping stations, etc. This is a service provided by the public telecommunication system. The data is considered very useful for the allocation of maintenance crews. They can respond faster to equipment failures. It is also useful for further planning studies because of the available synchronized data on storage and flow propagation.

According to the definition given previously, these systems are not RTCS because they lack the possibility of direct local or remote action and because they do not adapt the drainage flows to these data, be it meteorological data (rainfall) or the receiving water quality.

A conversion from traditional to RTC operation requires drastic changes in sewer management. For example, automatic and remote operation of regulators does decrease safety for sewer maintenance crews unless special measures are provided. RTC increases structural risks due to more frequent surcharges unless special care is taken to check periodically the structural integrity of the UDS. RTC usually also increases sediment deposition. Many sewer managers with RTC in mind have been forced to simplify their UDS operation to static control, because day-to-day operation of the UDS would not adapt to the new approach. The following description includes some comments on the sometimes drastic changes in day-to-day operation.

Another major requirement before entering RTC is to define clearly the operational goals. Moreover, there ought to be a thorough evaluation of what really can be gained by RTC with respect to these goals, compared to the traditional static operation.

Finally, a decision aid system has to be used at least during the design stage of the RTCS but can also be helpful on-line (e.g. as a trainer or a user-friendly simulator). Otherwise operators might simply be frustrated by the amount of information entering a RTC centre.

The following description of the French RTCS includes non-traditional items such as:

- definition of operational goals,
- existing/planned capacities,
- decision aid system,
- effects of RTC implementation.

RTCS, according to the definition formulated in Chapter 2, are implemented in the Cities of Bordeaux, Marseille, Nancy, and the Departements Hauts-de-Seine, and Val-de-Marne. The RTCS of Seine-Saint-Denis is described in more detail below. Table 5 summarizes the characteristics of these RTCS.

Heavy flooding has been experienced in **Bordeaux** while upstream retention basins were not filled. As there does not seem to be a pollution problem for the Garonne estuary, the Bordeaux RTC project is mainly used to

Table 5 **Operational characteristics of real-time control systems in France: (planned) and existing**

City or County	Goals and attached means	Planned horizon	Survey of local stations—(planned) or existing: Total	Telemetering only	Under local control only	Within system control	Decision aid system: Off-line strategy research	On-line information processing	On-line strategy research	Change in sewer daily operation: New real-time crew	Workers' safety	Observation of deposit or degradation increase	Event replay
Bordeaux	Flood control with 3 peak limiting storage capacities	1990	19	15	3	1	Simulation of hydraulics with local control	(No)	(No)	On duty operators	No	(Yes)	(Not yet)
Hauts-de-Seine	Overflow frequency reduction to the Seine river (full use of interceptor capacity)	/	/	/	/	None	(No)	(No)	(No)	(No)	(No)	(No)	(No)
Marseille	(1) Overflow frequency to the Mediterranean sea beaches (full use of interceptor capacities)	1992	70	(65) 3	(5) 1	(5) /	Yes	(Yes)	(Expert system)	/	(No)	(Yes)	(No)
	(2) Flood control with 6 peak limiting capacities		21	(15)	(6)	(6)	(Yes)	(Yes)	(Expert system)	/	(No)	(Yes)	(No)
Nancy	Downtown flood control with 2 retention basins	1987	Approx. 30	Approx. 30	2	None	(Yes)	No	No	Speeded maintenance	No	(Unknown)	(No)
Seine-Saint-Denis	(1) Flood control with 2 retention basins (90,000 m^3 and 60,000 m^3) protection of a recreational facility against frequent overflows (up to 15 m^3/s), storm pollution abatement with 60,000 m^3 settling basin	1988	35	25	9	3	Yes: optimisation and simulation of hydraulics	Yes: (expert systems) in the future	Yes: optimisation	Speeded maintenance On duty operators (Inspection of construction and cleansing works)	Yes	(Yes)	(Yes)
	(2) Other catchments within the county	1988	44	29	15	/	Yes: simulation of hydraulics with local control	(Yes)	(Yes)				
Val-de-Marne	Water intake impacts, floods, surcharges with:									(Speeded maintenance) (On duty operators) Inspection of construction and cleansing works	(Yes)	(Yes)	(Yes)
	(1) manual control (construction works, pumping stations),	1992	(/) 22	(/) 20	(/) 2	(/) /	/	Yes	No				
	(2) supervisory control (off- and on-line storage),	1992	(45)	(34)	(8)	(3)	Simulation of hydraulics	(Yes)	(Yes)				
	(3) as for (2), (flow derivation only),	1992	(21)	(15)	(4)	(2)	(As above)	(Yes)	(Yes)				
	(4) local flow control to sewage treatment plant	1992	(15)	(4)	(11)	(/)	(As above)	(No)	(No)				

reduce these floods. Off-line simulations of automatic control have been carried out. They showed the efficiency of automatic unit process control (see Chapter 3 for definitions) for a retention basin. It was decided to have a unit process RTCS implemented for this basin. The other basins are still manually and locally operated, i.e. crews are dispatched to the basins whenever heavy storms are forecast. No on-line decision aid system is planned. However, use of radar information on storm activity is to be implemented on a daily basis. Presently, a study is under way on how RTC affects sediment deposits in sewers.

In the Departement **Hauts-des-Seine**, overflow gates to the Seine River required automatic control. This is to reduce the frequency of combined sewer overflows and to avoid river water entering the UDS at high flow levels. The stations are controlled locally. As yet, the performance of this local RTCS has not been simulated off-line. No evaluation of the routine operation has been carried out. However, the management is aware of a need for a new design of the existing RTCS.

The City of **Marseille** experiences frequent beach and harbour pollution due to combined sewer overflows and extensive flooding during heavy Mediterranean storms. Off-line modelling of these phenomena has been started. A monitoring network including five remotely transmitting rain gauges was installed. Two regulator stations (one overflow gate, one retention basin) will start operation in 1988. During the preparation of the project the UDS management became aware of the excessive amount of information which will be received during a critical event. Therefore, a decision aid system, based on the concept of expert systems is going to be developed. Management is also aware of the operational changes with respect to safety, training, etc. The Marseille RTCS will be a state-of-the-art system including drastic changes in operation and work organization and extensive environmental monitoring and modelling before implementation and evaluation after start-up.

The City of **Nancy** experienced heavy flooding in the downtown area, after which two large detention basins were constructed within that area. Moreover, the District of Nancy is aware of the potential benefits RTC can offer to other public services such as public transport and drinking water distribution. Therefore, a comprehensive RTCS has been installed that allows the operation of the UDS and the water distribution using the same control computer. The two basins are locally controlled with central supervision. Global control mode has not yet proved useful. The district management is presently concentrating on rain and flow measurements including laboratory and field testing. Also, a radar for storm surveillance is under evaluation. Up to now no decision aid system is envisaged. Day-to-day UDS operation was only marginally affected by the RTCS.

The Departement **Val-de-Marne**, located south of the Departement Seine-Saint-Denis, is planning a RTCS to overcome basically the same problems as are occurring in its northern neighbouring Departement. As an additional problem, some major water intake structures of the City of Paris water supply system are located just downstream of the Val-de-Marne catchment. According to the Clean Seine River Program operation of the UDS has to be drastically improved. One of the first actions is a RTCS for a new interceptor serving the new Valenton treatment plant.

The existing system features a monitoring system of 12 digitally recording rain gauges, 40 digitally recording flow gauges and a radar image processing system. Two pumping stations and three overflow structures are under local control. There is also an on-line communication link to the planning and operation divisions including a database to improve planning and operation. Off-line simulation of the controlled UDS is underway. The project (Fig. 65), due for completion in 1992, will cover items such as:

- reduction of flood and pollution risks due to construction and maintenance throughout the UDS,
- flood and overflow control in two subcatchments,
- limitation of flows into the Valenton interceptor,
- development of a decision aid system and new guidelines for day-to-day operation.

8.6 United Kingdom real-time control systems

In the UK it is estimated that over 70% of the sewer systems are combined and that in England and Wales alone there are over 10,000 overflows of which many are considered unsatisfactory. The need to improve the quality of rivers and bathing beaches has led to a number of sewer schemes employing RTCS.

Along the **Tyneside** over 200 outfalls discharge crude sewage into the river. Because of the flow patterns and tidal effects it was found that raw sewage was taking up to 10 days to clear the estuary. The river water quality suffered and the neighbouring beaches were affected by sewage deposits. A scheme was initiated to clean up 32 km of estuary and 14 km of beaches by constructing sewers on either bank of the river Tyne to intercept the old outfalls. Sewage is now conveyed by gravity and pumping mains to the new treatment works at Jarrow and Howden. The majority of the old outfall pipes have been retained as overflow pipes. Actuated penstocks (i.e. sluice gates) control the flow of sewage into the interceptor sewer and at times of heavy rainfall the interceptor is used for storage. All the pen-

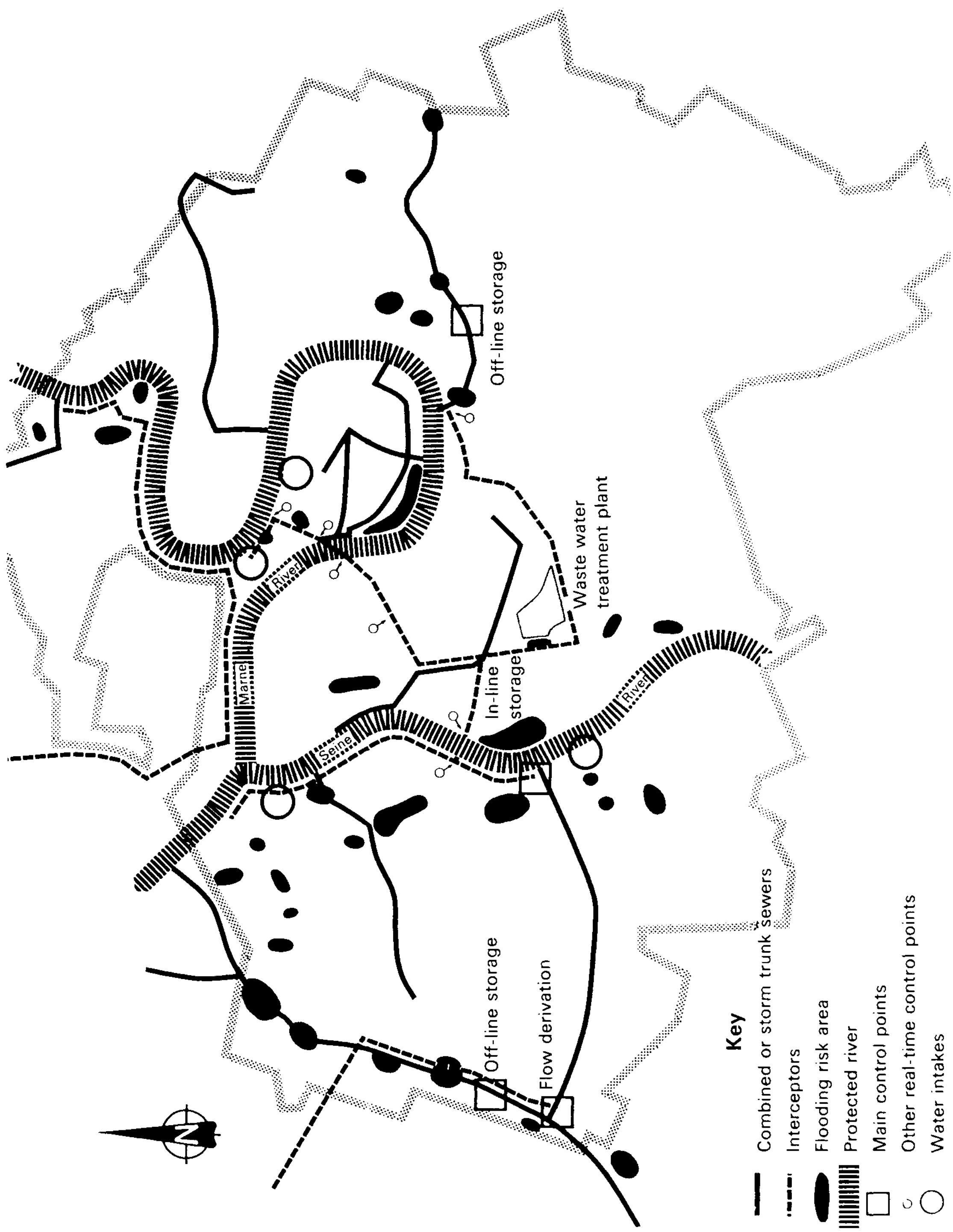


Fig. 65. The projected Val-de-Marne, France, real-time control system (1992).

stocks, siphons and pumping stations are controlled from the telemetry centre at Howden.

Similarly in **Liverpool**, where 24 outfalls, discharging crude sewage into the Mersey estuary, are to be intercepted by a deep sewer. At each interceptor site an on-line storage tank is to be constructed with a calibrated vortex outflow device discharging sewage into the interceptor sewer. Controllable penstocks allow the storage tanks to be activated and isolated. The overflow pipes are below high tide level and estuary water has to be prevented from entering the tanks.

In the Black Country to the west of **Birmingham**, the poor quality of effluent from a number of old sewage treatment works has led to an unacceptable water quality in the river Tame. To address this situation, the Severn Trent Water Authority is constructing a trunk sewer system to enable all but two of the works to be closed and the flow transferred to Minworth Water Reclamation Works, where treatment capacity is available. The catchment served is some 1500 km^2 and, as such, can give rise to storm flows which cannot be coped with by the trunk sewer system. There may be value in using a RTCS to optimize trunk sewer capacity and minimize impact on the river from sewer overflows by using balancing and inlet control flow gauges. Level sensors have been installed in the sewer, together with water quality monitors in the river to provide the information necessary to model the system, predict the value of options and design whichever system of control and operation is proven to be necessary.

RTCS have been employed at a number of sea outfalls, i.e. **Weymouth** and **Grimsby**, where sewage, following preliminary or partial treatment, is pumped up to the headworks. Discharge through the sea outfall is by gravity. The optimization of the pumping regime to prevent flooding is the main objective, but in addition other objectives are sought, such as initiating flushing velocities periodically to scour the pipe of deposits or saline water, control the treatment processes, and at the same time minimize the energy costs.

8.7 Japanese real-time control systems

In Japan, only a small amount of research deals directly with RTC for UDS, but more deals with some aspects of RTC. For example, research has been carried out on the real-time forecasting of rainfall and on gathering databases and constructing data acquisition systems.

These studies, which yielded useful results with respect to the design of UDS, are also applicable to evaluate real-time control methods and devices. The data are already useful for supplying urgent information in the case of heavy rain and flooding.

The practical necessity for implementation of RTCS will force research to advance. Several large and small detention systems, which utilize natural basins and artificial tanks, have been constructed including the necessary data acquisition systems. Management reports are available about the operation and maintenance of these systems. However, many of them deal with planning and simulation but only a few deal with practical applications and results. In the future, more such systems will be constructed and research will continue by means of the data gathered. Furthermore, it is absolutely necessary to proceed with research about the basic theory of designing RTC in UDS to estimate effect before actual implementation.

Urban drainage in Japan usually suffers from two problems. One is the lack of UDS: the percentage of population served by UDS was about 35 % in 1985. Another is the lack of transport capacity in existing UDS which is caused by urbanization. Detention and system supervision are used to solve these problems.

Now remote and automatic systems for centralized supervision are being introduced into urban drainage. Most existing control units are equipped with old types of regulation and monitoring devices. Such systems require great expense for labour. The remote and automatic RTCS for centralized supervision are expected to cut down operating and maintenance costs. The goals, which should be achieved by this centralization are:

(1) communication among different control units and departments:
   - communication among organizations; e.g. warning alarms for flooding from an administrative organization,
   - information gathered to a control centre from subsidiary centres in the basin,

(2) efficient management of the overall system:
   - coordination of the local control units (global control),
   - alleviation of flow impacts for the control of treatment plants,
   - control of the treatment plants,
   - detection of accidentally bursting or leaking sewers and adaptive controls to contain the emergency,

(3) build-up and management of the database:
   - database for producing and modifying the manuals about unit process and supervisory control,
   - database for investigation and research about the improvement of control and planning methods.

The first and third goals are principal goals for any type of UDS. However, only very few systems already have efficient control of the overall system.

A typical RTCS is the supervisory control system of the **Neya River Basin**. Similar systems are located in **Tokyo**, **Okayama**, etc. This system consists of two treatment plants and 17 pumping stations, in a catchment of approximately 270 km^2. The data, which include water levels in the sedimentation tank, the number of operating pumps and the valve operation in the pumping stations, are gathered by the telemetry network using public telephone lines. The most important goal is to prevent flooding which occurs in urban areas once every few years. The operation of the UDS, therefore, needs to be linked to the systems of other organizations such as the river department or the rescue department. As a result, the UDS management is also required to supply its data to other information centres.

Communication among several departments allows control of the overall system by also using the regulator units of other departments. Examples of such control units are the detention basins and the gate at the junction of two rivers. By coordinating these units, the operator may find additional control capacity compared to what would be available in the local system only.

The global control of the UDS is expected to benefit from a connection with two other information systems. These are the meteorological information system and the regional information system. The latter system is a database about a set of natural and social data such as altitude, land use, road and river networks and other information. The regional information system covering all Japan has already started its service. Some cities (**Tokyo**, **Osaka**, etc.) have their own systems. The meteorological system is equipped with the Radar and AMeDAS (Automated Meteorological Data Acquisition System). 17 radar sites are presently operating in Japan covering all the country and the coastal waters. AMeDAS is also equipped with remote monitoring stations over all Japan (one station per 289 km^2). There, rainfall precipitation, wind velocity and direction, temperature and atmospheric pressure are measured. These data indicate the spatial distribution of rainfall and allow the tracing of the paths of cloud masses and precipitation. By using these data, the Japanese Meteorological Agency developed rainfall forecasting models and, in the near future, will commence releasing the information of forecasted rainfall for a time horizon of several hours. These forecasts are very useful for RTC of UDS.

Cheap personal computers can reduce the investment cost of computer units. For example, in the City of **Osaka** control units were equipped with a computer to execute control of a neighbouring relay pump station remotely and automatically. However, application was limited to small-scale units which consist of a single pump located near to other manned control units. Thereby, in cases of failure of the automatic system, the staff is able to take over manual operation.

It was found that equipment for remote automatic control needs to have two essential properties: easy start-up facilities and easy maintenance. Therefore, programs have to be user-friendly, hardware should allow for modular exchange of parts, the system should be hooked up to a duplex data transmission system, and backup energy supply should be available at all times. Such a system of local units is then tied into the supervisory RTCS described above.

In the **Kanagawa District** a demonstration system was installed featuring water level and velocity sensors and a fibreglass data transmission network. The system is to monitor sewage flows within a large urban drainage area. Operators can use this data to override local control functions if need be. In-line storage can also be activated if this kind of flow information is available. Since such a data transmission system is rather expensive it is proposed to use it for other purposes as well.

8.8 Cases

8.8.1 DETROIT, MICHIGAN, USA

The Detroit Metro Water Department (DMWD) serves 11 communities with 35% of the Michigan population, and large industrial inflows (Watt *et al.*, 1975). The rather flat sewers divert CSO into the Detroit, Rouge and Huron rivers through 110 outfalls. The controllable in-line storage, related to the entire catchment area, is only 8.3 m^3/ha. DMWD operates an extensive flow level monitoring system at some 250 sites using very simple and apparently reliable air pressure cells. Operation routinely relies on National Weather Service radar data which allows to pump down the water level in the system up to three hours before an approaching storm starts to rain over the catchment. The conditions of 70 tide gates are monitored to detect blockage and other operational problems. The real-time control system is operated in 24 hour supervisory control, together with the water supply system. A reduction in CSO duration from 5% to 1.3% has been achieved. Central automatic control is not implemented.

8.8.2 SEATTLE, WASHINGTON, USA

The Municipality of Metropolitan Seattle has operated a real-time control system for approximately 15 years to reduce CSO into Puget Sound (Pacific Ocean), Duwamish River and Lake Washington (Leiser, 1974). The system can be run in local automatic, central supervisory, or central automatic control modes. Original plans to adjust the 'control matrix' strategy as a function of local rainfall have not been implemented yet. Average CSO volumes for different modes of control are estimated as follows: 7.0 million m^3 for 'no RTC', 4.4 for local control, 1.9 for central automatic control, and 1.5 for central supervisory control. Planning is currently under way to upgrade the system, and replace the old computer hardware by state-of-the-art technology. Because of the success of the real-time control system, plans for separation have been deleted. Additional benefits of the system, according to the operational personnel, have been reduced flooding and monitoring and source detection of gasoline spills.

8.8.3 CLEVELAND, OHIO, USA

The Northeast Ohio Regional Sewer District operates major trunk sewers, interceptors, and treatment plants for the City of Cleveland and 33 suburban communities (Buczek and Chantrill, 1984). Before remedial measures, almost every rainfall created CSO at some 600 overflow points into the Cuyahoga River and Lake Erie. The real-time control system was initiated in 1975 with three regulators, and a greatly expanded system became operational in 1983. The system now controls some 50% of the original CSO volume. Operation up to now has been local automatic with central supervision. Centrally adjustable control actions are actuated by on-site microprocessors. The control centre has a back-up computer which is intended for later simulation and optimization of the control strategy. Operator interfaces include colour CRT's with graphic displays, 'trending' software, and alphanumeric and dedicated keyboards. In terms of hardware, this system is one of the most advanced in North America.

8.8.4 LIMA, OHIO, USA

The City of Lima, Ohio operates a real-time control system for its combined sewer system that covers some 15 km^2 (Brueck *et al.*, 1982). It and Seattle are the only two RTCS in the USA with central automatic operation. However, both systems do not employ real-time modelling of the rainfall/runoff process. In Lima, eight sluice gate regulators are operated from the central control room. The system has been operating for some five years without major problems. The treatment plant inflows are not only regulated during wet weather but also during dry weather by the control gates. After storms the system is automatically flushed by opening interceptor gates beginning downstream. After working hours the system runs automatically without supervision.

8.8.5 SEINE-SAINT-DENIS, FRANCE

The RTCS in the Departement Seine-Saint-Denis (Fig. 66) has gone through a stepwise implementation which gradually changed the many aspects of day-to-day UDS management and operation. The size of the county is 256 km^2. Numerous local floods have been experienced. Pollution problems due to combined sewer overflows exist for recreational ponds as well as at the outlet locations into the rivers Seine and Marne.

For the UDS management it was obvious that a new kind of operation was needed: flooding occurred during construction work and accidental pollution events could not even be detected let alone be controlled. RTC seemed to be the only way to handle the phenomenon of localized storms in such a large UDS.

At present, with approximately half of the projected hardware installed, the Seine-Saint-Denis RTCS features:

- a telemetered monitoring network consisting of 12 rain gauges, 20 flow gauges, 30 overflow gauges,
- local monitoring stations, i.e. 8 rain gauges, 80 flow gauges, 20 overflow gauges,
- 20 pumping stations under local control with central supervision,
- a real-time information retrieval and alarm system at the home of on-call operators.

This system is still under expansion. One of the six main drainage districts is now experimentally under global control mode. Its decision aid system is designed to cope with the large amount of available information, with short-term rainfall forecasting and flow propagation, with the evaluation of the best control strategy and its presentation to the operator. Additionally 10 units such as diversion structures and retention basins are controlled separately.

Day-to-day operation was affected by the RTCS in that new safety guidelines had to be implemented to avoid accidents to maintenance crews caused by interference of central control commands. An express maintenance service was established which would be on call during risk of heavy storms. A separate RTC group was established, again on call during storm periods.

8.8.6 WERVERSHOOF, NETHERLANDS

The sewage treatment plant of Wervershoof provides treatment of the wastewater of several villages and cities in the region of West-Friesland (Province of North Holland), covering an area of approximately 250 km^2.

The plant is connected to the urban areas by means of a system of pressure mains, conveying the sewage over many kilometres (Fig. 67). The treatment plant at Wervershoof is of the oxidation ditch type (caroussel) with a biological capacity of 100,000 population equivalent and a hydraulic capacity of 3600 m^3/h.

Soon after the plant was put into operation in 1980, it appeared that in the near future the hydraulic capacity would no longer be sufficient. This was mainly due to a rapid decrease in the occupation of dwellings in the old cities (leading to an increasing discharge per inhabitant according to the specific Dutch license system). The sum of the installed pump capacities of the complex system of drained areas (Fig. 68) determined the hydraulic treatment capacity which would be necessary in the future (approximately 5800 m^3/h).

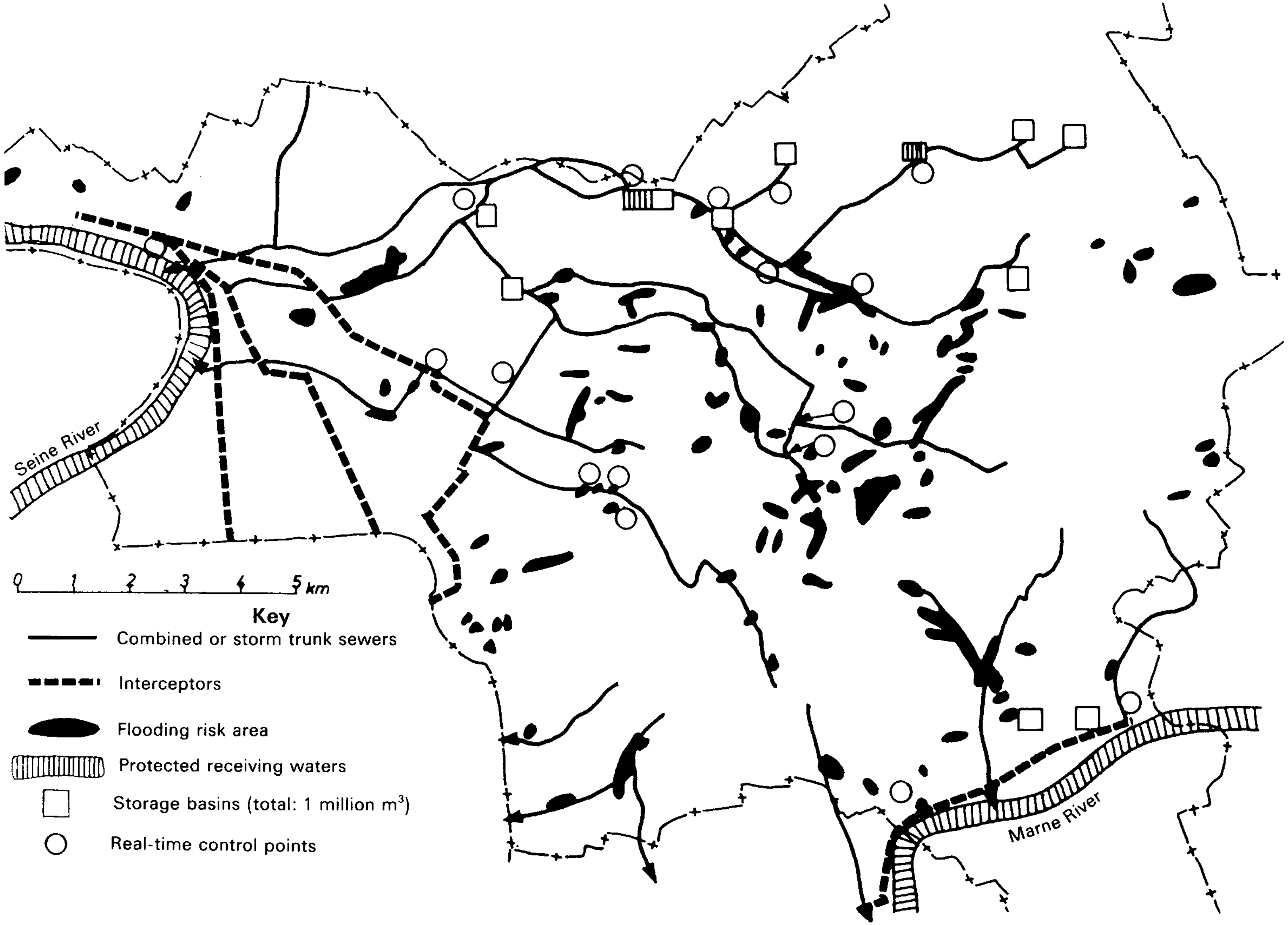


Fig. 66. Seine-Saint-Denis, France, real-time control system.

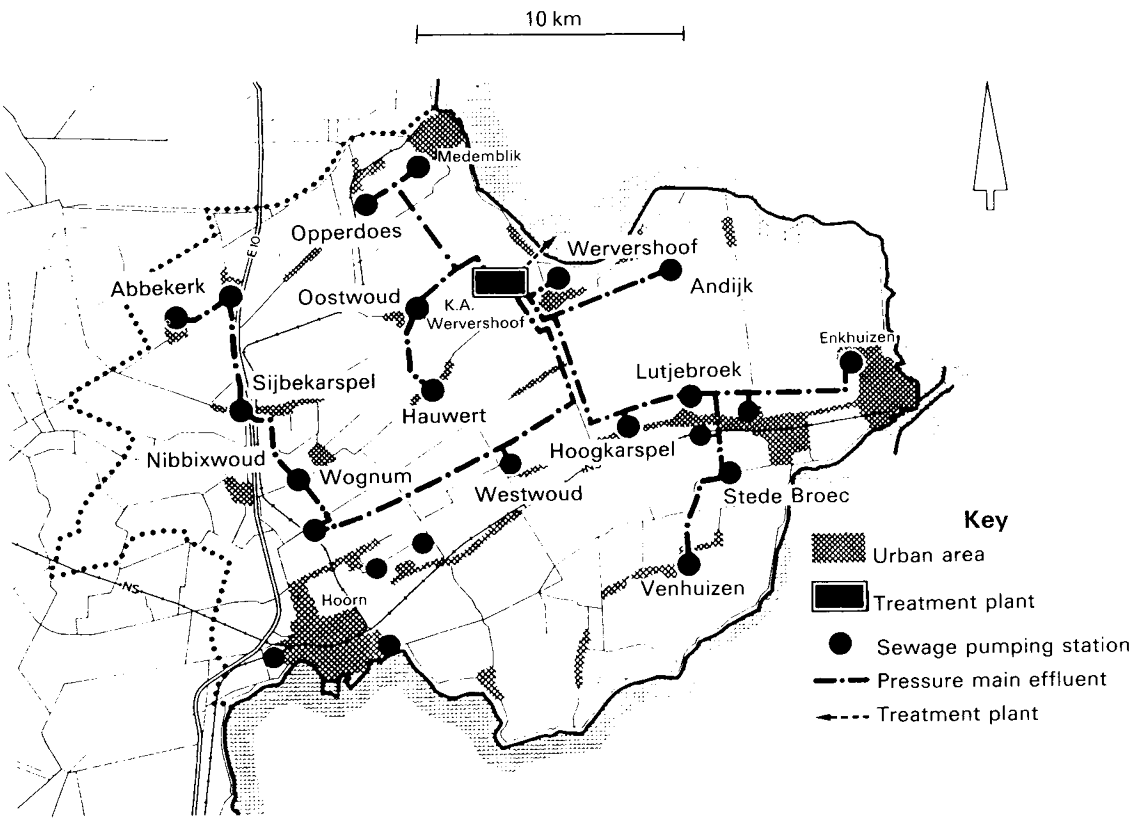


Fig. 67. West Friesland sewerage system—overview of pumping stations and pressure mains.

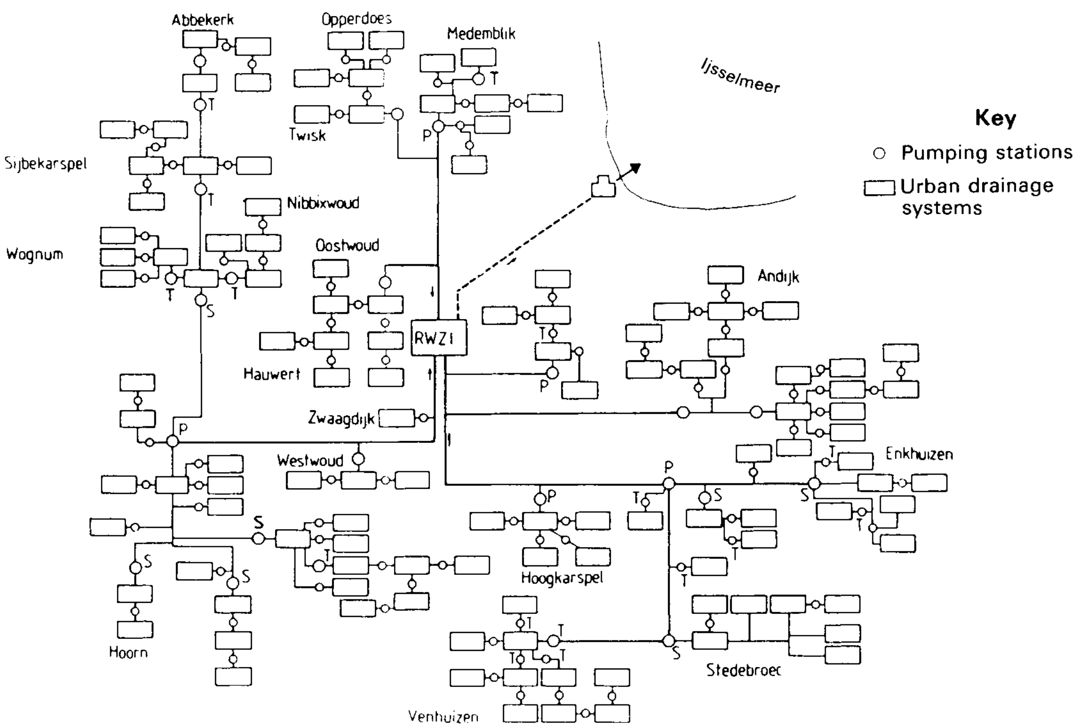


Fig. 68. West Friesland sewerage system.

Instead of expansion of the treatment plant, a solution was found in making use of the experienced spatial variations of precipitation in that area. After extensive studies it was concluded that the hydraulic reduction to be gained from this phenomenon would be 30% of the future hydraulic capacity (computed for the statistically and geographically most unfavourable rainfall distribution). To really make use of the rainfall distribution, a centralized control system was necessary to determine, on the basis of water level measurements in the different drainage systems, the optimal combination of in-line storage and discharge capacity of the pumping stations to the treatment plant. This is to be done under the conditions of not flooding the treatment plant and, at the same time, not increasing the number of overflows of the sewer systems into the surface water.

The implemented system has the following functions:

- quantity control: reduce hydraulic loading of treatment plant to avoid flooding of the plant as well as additional combined sewer overflows,
- quality control: use the RTC system as an instrument to direct sewer overflow to less vulnerable locations of the surface water system,
- emergency control: execute predefined scenarios in case of emergency,
- information processing: monitor and process pumping data to improve the management of the sewage transportation system.

The control system is set up as a fully automatic and centralized controlling system. The control system is implemented on a mini process computer connected to a telemetry network with both fixed and dialled connections. From a total of about 125 pumping stations in the area, 28 have been selected to be part of the telemetry network. An overview of the hardware and software set-up is given in Fig. 69 and Fig. 63.

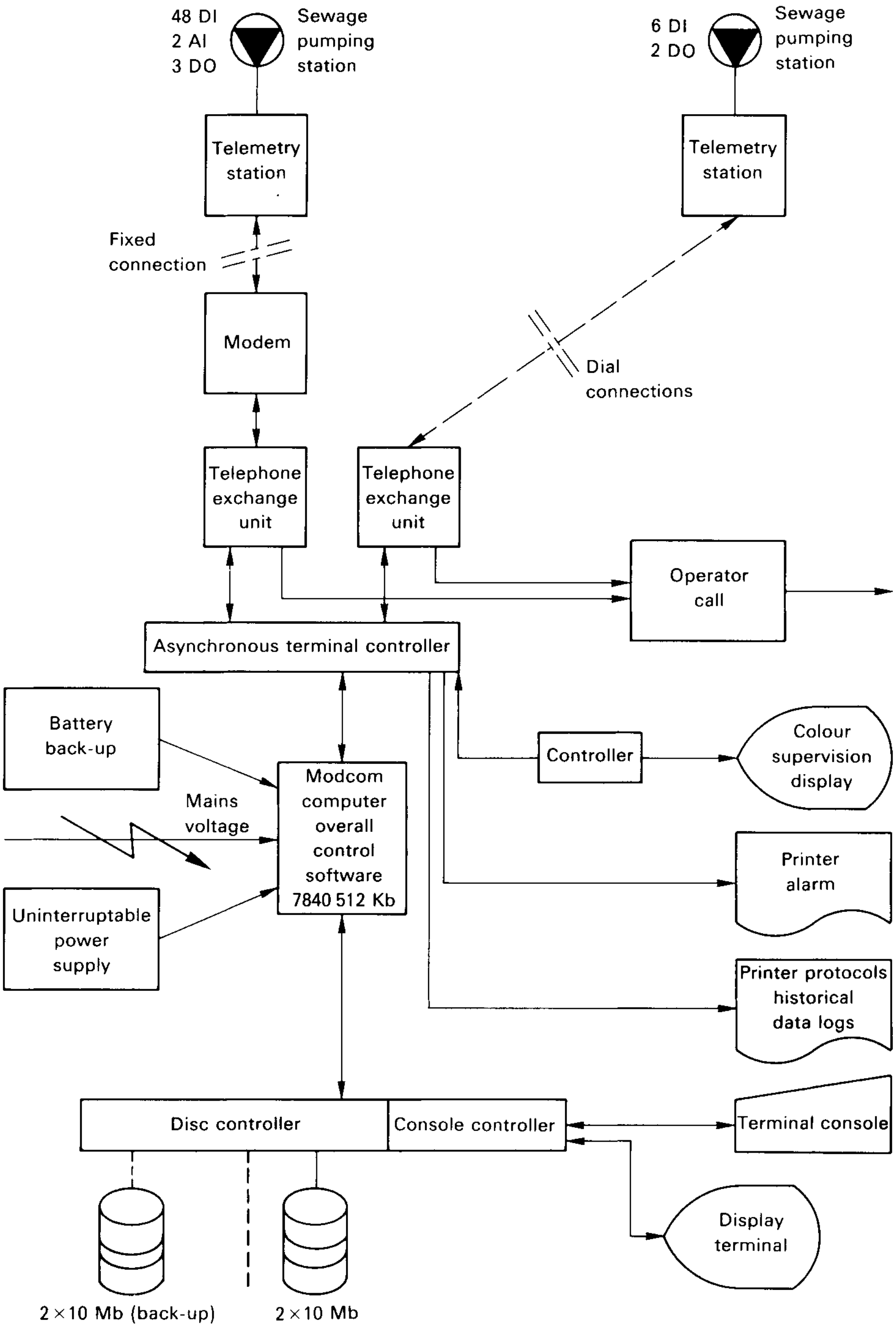


Fig. 69. Hardware configuration of West Friesland RTC system.

Control action is based on the following elements:

- water level measurement at the pumping stations,
- signalling of pumping data and overflow data,
- computation of a variable incorporating a uniform water level and a weighing factor based on overflow conditions and vulnerability of the surface water,
- computation of a priority list of pumping stations and capacities to be selected for discharge,
- keeping the records of the pumps, the pumping stations and the pressure mains,
- optimization rules on the basis of the priority list and the historical situation to guarantee maximum discharges to the treatment plant (up to the hydraulic capacity), minimizing the number of overflows and maximizing the storage used when the treatment capacity is reached.

The control system has been in uninterrupted automatic operation since May 1983 with very satisfactory results. It is unique in the way it operates and in the way it has been implemented.

8.8.7 ARNSBERG, FRG

Arnsberg is a city of 75,000 inhabitants which extends over 30 kilometres along the River Ruhr. The City of Arnsberg is responsible for collecting the wastewater from 25 municipalities. Responsible for the treatment of all wastewater is the 'Ruhrverband' which is the Sanitary District of all communities draining their wastewater to the river Ruhr. The three major treatment plants serve an area of 4,000 ha with a population equivalent of about 100,000 people. The new treatment plant 'Neheim II' which is under construction will serve another 75,000 population equivalent. With its completion in 1988 two older treatment plants will be closed and parts of them will be used for the storage of combined sewage. The collection system consists of both combined sewers and separate sewers. Eleven flow regulator stations are already in operation (locally controlled) together with the necessary peripheral devices (ultrasonic level

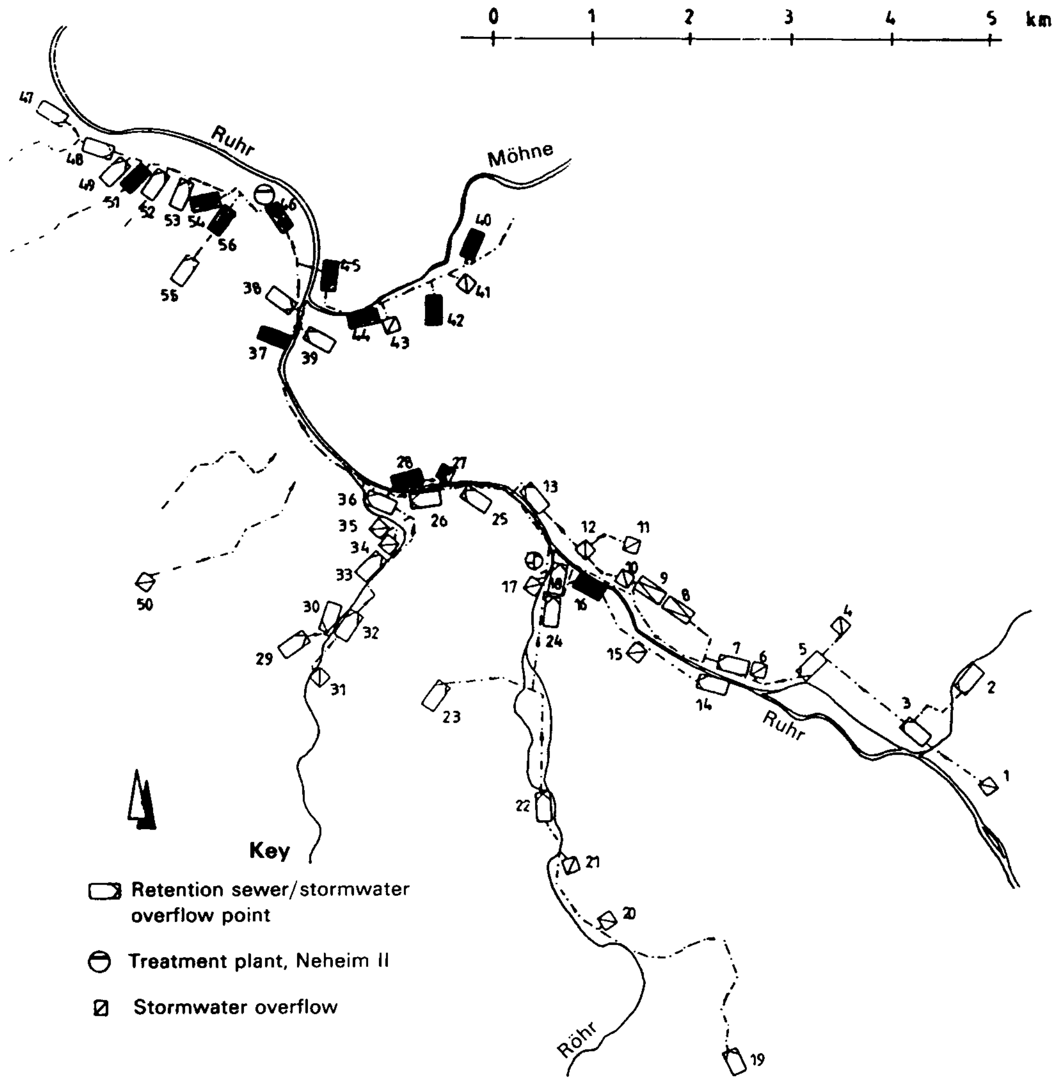


Fig. 70. Network scheme of the sewer system in the catchment area of the Neheim II treatment plant.

sensors, capacitive probes, Venturi and electromagnetic flow meters, vortex valves with pressure sensors, automatic discharge controllers, pumps, electrically operated gates and weirs).

With the completion of the 'Neheim II' plant in 1988 all regulator stations can be under remote automatic control to optimize the storage and overflow of storm runoff. At present, the Urban Drainage Department of the City of Arnsberg, in co-operation with the Ruhrverband, are developing a strategy to control this system. The system is planned to have about 35 real-time controlled regulator stations in the year 2000 (Fig. 70). This is an equivalent of about 28,000 m^3 storage, more than 90% being in-line storage. The costs to complete the RTC system including the necessary hardware for telemetry and regulators are estimated to be about five million DM for the next 12 years.

8.8.8 WEYMOUTH, UNITED KINGDOM

The Borough of Weymouth and Portland, acting as sewerage agents for Wessex Water, operate a RTCS to drain a contributing area of Weymouth of 55 ha and a population of 47,000 in winter to 72,000 in summer. Sewage arrives at the Radipole Pump Station under gravity in two trunk sewers of 1.5 m diameter each, (Fig. 71). Preliminary treatment (screening, maceration and grit removal) is undertaken prior to pumping.

Two dry weather pumps (each rated at 375 l/s and a power consumption of 175 kW) and two storm pumps (each rated at 725 l/s, power comsumption 323 kW) pump partially treated sewage up to the headworks via a 800 mm diameter pressure main for dry weather flow and 1100 mm diameter main for storm flows. Each pipe is 1700 m long and housed in the same tunnel. Two smaller overflow pumps at times of emergency will pump into the harbour backwater.

The 800 mm rising main is normally kept full but the 1100 mm main, after use, has to be drained down to avoid septicity and corrosion. Unfortunately, the topography does not allow the 1100 mm main to drain back to Radipole. Another small pumping station is sited at the low point of the 1100 mm main to empty the storm water into the 800 mm main. Finally the headworks discharge sewage by

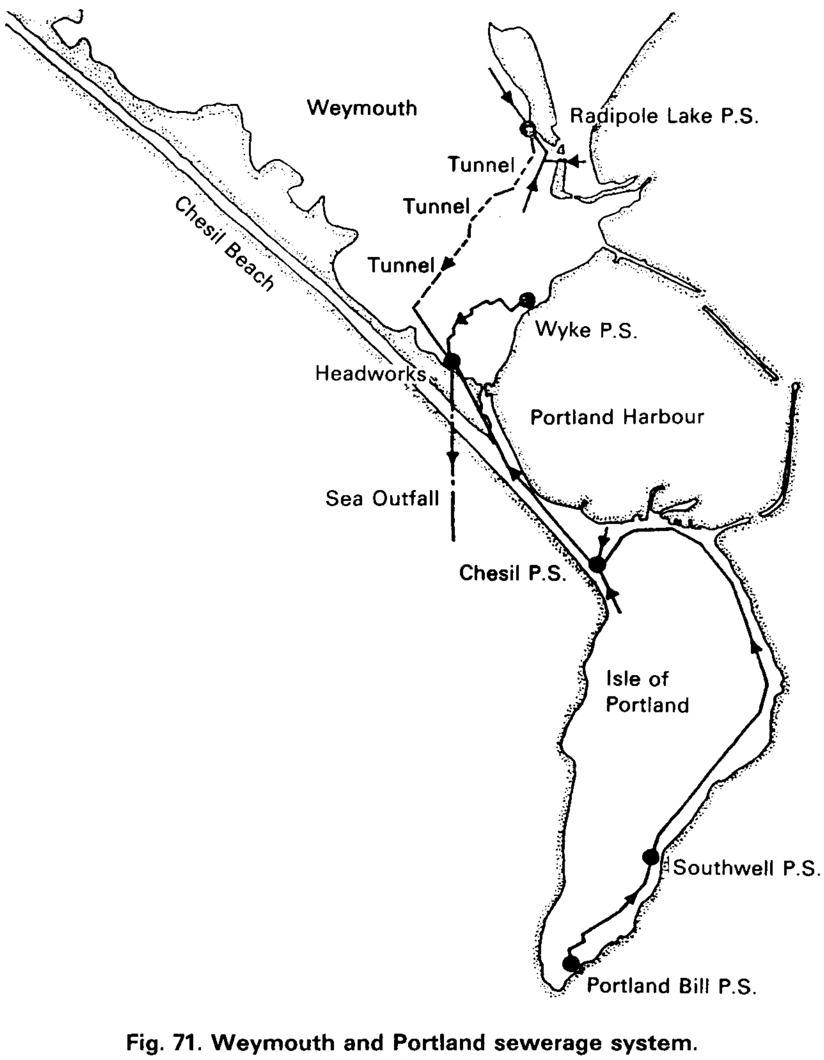


Fig. 71. Weymouth and Portland sewerage system.

gravity through a 2700 m tunnel out to the sea.

Total storage, consisting of the Radipole Pump Station wet well and the two 1.5 m diameter trunk sewers, amounts to 3000 m^3. The main objective is to prevent urban flooding but with RTCS, including a forecast of inflow to the pumping station, it was anticipated that savings in energy could be achieved. In a typical year it was estimated that savings of 14 to 20% could be achieved over a level only (i.e. local) control system. The pay-back period for the additional cost of the control system was less than 3 years.

The RTCS with optimizer control at Radipole runs every 4 min receiving telemetered information on rainfall, sewage depths, flows in the rising mains and pump stations every 2 min. The drainage area is divided into three sub-catchments each with a tipping bucket rain gauge and the time of concentration for the total catchment is approximately 140 min. A model is used to predict rainfall, run-off and inflow to the pumping station at 1 min intervals up to the end of the forecast period (1 hour). This forecast is updated every 4 min. Prior to selecting the most economical pumping regime to negotiate a route through the 'tunnel of operational options' to the end of the forecast period, the program examines the status of the electricity consumption and storm water rising main and the storage available.

The local system runs automatically for 24 hours a day with alarms and system status only available at a central control room. The software also controls the treatment processes, i.e. raking of screens and the weekly flushing routine through the sea outfall pipe.

9. Literature on real-time control and related topics

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