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Integrated Approaches in Urban Storm Drainage: Where Do We Stand?

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ABSTRACT / Integrated approaches to urban stormwater drainage management are being increasingly advocated as necessary for advancing more sustainable and holistic management of urban water environments. In this paper, the status of integrated approaches in the management of urban stormwater discharges to receiving waterways is summarized. The starting point of the paper is with the recent scientific contributions, revealing that integration is being pursued and implemented predominantly at two conceptual levels. These include 1) integrating the technical system with the receiving waterway environment, and 2) considering the interaction and influence of the human system with the technical system through processes such as stakeholder and public participation. Additionally, it is argued that the evolving shift towards the implementation of water-quality-based strategies advances the need for further development and application of integrated models and approaches. The cases of online physically based models for predictive control and integrated source control and public participation are presented as examples of such ongoing developments in pursuit of integrated urban stormwater management.

The use of the adjective ''integrated'' in conjunction with the investigation of environmental problems inevitably creates an aura of high aspirations by promising the use of new approaches as opposed to previous practice. Quite frequently, studies on environmental issues claim to be integrated. However, when looked upon in more detail, it is apparent that the ''degree of integration'' in these investigations differs widely. The reason is that the term ''integrated'' is, in itself, vague and the definition of it stems more from a personal perspective rather than from objective criteria. For example, an integrated assessment of an environmental problem should cover all *relevant* issues, but relevant to whom and with regard to what? Unless some distinct criteria are stated, this choice is subjective and difficult to transfer to a system with different boundary conditions.

Looked upon from a general point of view, the word ''integrated'' has the meaning of completeness. It suggests that, for a given problem, all issues of influence are being integrated over a plane or along an axis (for example, over space and time, within social contexts, economic frameworks or institutional policy paradigms, etc.). However, global integration is neither necessary nor feasible when investigating specific and mostly regional problems. A compromise with respect to the holistic aspect of an investigation is required in order to obtain practicality. Hence, prerequisite to an integrated approach is the identification of the ''axis and planes'' in which integration needs to take place.

In this paper, we discuss the state of the art with respect to integrated approaches in the field of the centralized urban waste and storm water system. Following the arguments from above, the primary question to be tackled is the definition of the scale of an

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*Author to whom correspondence should be addressed; *email:* wolfgang.rauch@uibk.ac.at approach that we declare as integrated. From recent contributions to this topic (see, for example, Proceedings of Interurba II 2001, Novatech 2001), two dominant areas can be identified where integration is pursued within the urban storm drainage field:

- Integration of the drainage system.

Historically the construction and operation of municipal drainage systems has been driven by the objectives to 1) maintain public hygiene and 2) prevent flooding. Only later the aspect of pollution control became important and treatment facilities introduced to preserve the integrity of the receiving aquatic ecosystem. The challenge today is to move from such individual considerations of system performance to an integrated management of the urban drainage system comprising the sewer system, the wastewater treatment plant and the receiving water. The most recent approaches even take source generation at the household level into account (see, e.g., Rauch and others 2003). The implementation of management strategies requires numerical tools to predict the behavior of the complete system under historical and future scenarios.

Note that this issue is dominant in combined sewer systems and of less interest in separate storm and sewage systems. In the latter case, the problem is with assessing the relation between land use and urban storm drainage.

- Integration of the technical system and the public.

If the idea of integration is carried further, socioeconomic issues need consideration as well as the technical installations and the subsequent implications to ecological systems. Economic aspects play a major role in urban water management. The social function of water and the relationship between the technical and human systems is becoming increasingly recognized. In recent years, it has become clear that source control solutions contribute to moving responsibility from the public system to the individual. However, the apparent difficulties in managing and monitoring the performance of these small-scale solutions when imposed upon an individual have strengthened the incentives towards a more integrated approach. Recently proposed methods and solutions use the concept of stakeholder and public participation. The idea is to move away from traditional top–down decision making and involve stakeholders and the public in the planning process and in the selection of management techniques. With such approaches, it is assumed that improved community awareness and learning will lead to changes in social practices and behaviors.

This paper outlines the current status and perspectives in applying integrated approaches as outlined above in the centralized drainage of stormwater from urban areas. The paper is based on 1) work presented recently at international conferences, and 2) extending discussions of the consequences of the shift from an emission- to a water-quality-based perspective for integrated modeling, and with regard to future needs for the development of online models for optimizing the systems performance.

Development of System Integration

Present-Day Design and Management of Urban Wastewater Systems

In current urban wastewater systems, the subsystems including the *sewer system*, the wastewater treatment plant (*WWTP*), and *receiving water* are designed, optimized, and operated independently as highlighted in various publications (for example, Harremoës and Rauch 1996, Rauch and others 2002a, Erbe and others 2002), The transfer across the interfaces is characterized by static rules. For example, the flow to the WWTP under wet-weather conditions is limited to a value on the order of twice the peak dry-weather flow, and combined water is discharged to the receiving water or to a retention tank when the upstream flow rate becomes higher than a threshold value or—somewhat more complex—the number of combined water overflows (CSO) per year is restricted to a certain number.

The processes in the WWTP are often controlled, whereas real-time control in the sewer system is far more unusual. In integrated control technology (Schütze 1998), information from the entire system based either on measurements or on predictive simulations is used to take control actions. A typical example would be that the flow in the sewer system and the processes in the WWTP are controlled according to simulation-based predictions of the receiving water quality. Integrated control technology is not readily available, but is implemented only in a few test cases.

The interface to the receiving water is hardly considered at all. In many countries, the systems design and operation is driven by a rigorous emission-based approach; therefore, the design depends on the characteristics of the urban catchment rather than on the capacity of the receiving water.

Case Studies on Integration

Up until recently, only a few experimental large-scale case studies have been performed because of the enormous logistic and personnel requirements. In the study of Gujer and others (1982), 40 people were involved in ''tracking'' and detecting various compounds transported through the wastewater system from the point of rainfall to the receiving water environment during a storm event. The study revealed various interactions between the subsystems over space and time. For example, the compounds released through the WWTP effluent during dry-weather conditions are adsorbed by particles and settle on the river bed, where they erode during wet-weather flow, causing oxygen depletion. During the retention period in the river bed, hydrolysis took place and degradable combined sewer overflow (COD) was produced from heavily biodegradable COD. Additionally, it was shown that particles discharged to the river from the wastewater system were found in the groundwater with some delay, depending on the sorption characteristics in the soil.

The case study of Krejci and others (1994) showed that the receiving water quality repeatedly deteriorated as a consequence of urban stormwater impacts from CSOs, although the system was properly designed according to the guidelines. The reason for this impact was not only the wastewater system, but also the increasing drinking water abstraction, which resulted in a significant drawdown of the groundwater table after decades. Subsequently, the infiltration of groundwater into the receiving water as source of base flow in dry-weather periods was hampered. As a result, the dilution capacity of the receiving water with respect to impacts from CSO events decreased. Some virtual studies on options to improve the system's performance revealed that whenever a measure is taken in an individual subsystem, all linked subsystems may be affected, too.

Since 1995, a number of virtual studies on wastewater system integration were published, mostly by applying numerical models of the sewer system, the WWTP and—less often—the receiving water (see, e.g., Rauch and others 1998, Schütze 1998, Meirlaen and others 2001). Moreover, integrated control, as defined earlier, was numerically simulated with simplified models (Schütze 1998, Rauch and Harremoës 1999).

Integrative Approaches in Today's Regulations

National regulations include integrative approaches in some aspects, but do not integrate the entire system. In many countries it is common practice to consider stormwater infiltration as the primary option to deal with rainwater. This may be regarded as a source control and integrative measure that serves to recharge the groundwater aquifer, to reduce CSO spill frequencies and volumes, and to increase the fraction of sewage that is treated in the WWTP rather than being discharged as combined water via CSO structures.

The Urban Pollution Management (UPM) procedure, based on earlier Danish regulations and implemented in the UK in 1994 (FWR 1994), is a water-quality-based procedure for stormwater management. The pollution impact to the receiving water is considered via simplified models and statistical evaluation of extreme values, mainly focusing on oxygen depletion and on ammonia concentrations in the river. Also, the allowed impact to the river is defined via duration/frequency curves of certain concentrations. This procedure is used to design CSO structures and retention tanks, while the potential resulting from the interaction with the WWTP is excluded.

In most countries, stormwater management is primarily a question of either infiltration or retention, whereas in combined systems in The Netherlands and Flanders the first option is to increase the loading of the WWTP during wet-weather events. This procedure is still driven by static rules.

Switzerland has far-reaching regulations with regard to planning of wastewater systems by explicitly including the receiving waters morphology and ecosystem into the problem identification (Rauch and others 2002b). Enhancement of the receiving water quality may not only require investment into the improvement of the technical drainage system but also into the river system itself.

In the United States, regulation of wastewater discharges from all point sources is water-quality based (except stormwater for which pollutants must be removed ''to the maximum extent practicable''). Under current law, all point sources must comply with TMDL (Total Daily Maximum Load) discharge limits. These limits are set for each discharger in a river basin, taking into account all point and nonpoint source loads in the basin during both dry weather and wet weather. For the most part, these TMDLs are set by running the Hydrologic Simulation Program Fortran (Johansen and others 1984), which is a continuous simulation model driven by rainfall; it takes into account rainfall, infiltration, interflow, point and nonpoint source wasteloads, and streamflows. It calculates a time series of water quality concentrations at various locations within the watershed that are statistically processed and compared to the applicable water quality criteria for the various stream segments. Loads are adjusted to a level where the water quality criteria are met, and then the TMDL is set for each discharger. Unresolved issues involved with the application of this approach are 1) developing an accurate long-term record of rainfall

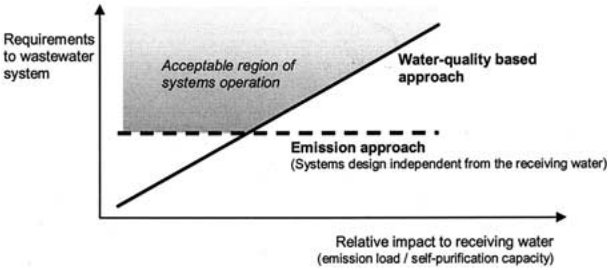

Figure 1. Combination of emission- and water-quality-based approaches depending on the specific impact to the receiving water.

that is spatially accurate over the watershed; 2) calibration of the model; and 3) the crude time scale, on which the approach is based, which does not allow for addressing the crucial acute pollution effects.

In the European Water Framework Directive, the primary goal of water management is defined as reaching good water quality in surface and ground waters. Among the core points, the combined strategy of emission- and water-quality-based approaches as well as the water management on a river basin scale are of vital importance for the development of the wastewater system. The conventional approach of the emission strategy applies only to situations where the impacts are small relative to the self-purification capacity of the receiving water. In turn, when the emission is high relative to the self-purification capacity of the receiving water, the water-quality-based strategy applies (Figure 1).

On the one hand, problems arise implementing the approach described above, because the cause–effect relationships between loads from the wastewater system and effects in the receiving water are not yet well understood. On the other hand, this goal-oriented approach offers greater degrees of freedom for improving the wastewater system's performance, because the choice of measures is not constrained by prescribed guidelines (Krebs 2000). Namely, the synergy potential originating from the interactions between the subsystems may be beneficially used.

The Need for Integrated Modeling and Integrated Control to Cope with Water-Quality-Based Standards

The water-quality-based approach will induce a shift in the perspective on urban water system development and consequently in the tools to be applied. It is now necessary to be able to link the measures taken in the wastewater system with the resulting effects on the receiving water quality or, conversely, to identify the most effective measure in the wastewater system to improve the receiving water characteristics identified to be unsatisfactory.

This requires a new dimension of 1) integration in systems operation and 2) integrated modeling tools:

1. There is still a lack of expertise on the wastewater-related effects in receiving waters. Synergy potential within the integrated system should be used in systems design and operation, such as process-depending increase of WWTP inflow during wet-weather conditions (see, e.g., Meirlaen and others 2001, Seggelke and Rosenwinkel 2002) or load-based real-time control to discharge the least-polluted combined water. Tools for tradeoff analysis of the dynamics and composition of the WWTP effluent and the CSO discharge must be developed, considering, for example, that COD in the two fluxes has different characteristics and causes different effects in the receiving water.
2. Only *integrated modeling* will allow evaluation and comparison of various options of system extension. Experience on the efficiency of the integrated system and of complex operation strategies, such as integrated control, is lacking. The significance of model-based online prediction of the system's behavior will increase with the need of integrated control, and respective developments are urgently needed as outlined in the next section.

Status and Perspectives in Integrated Modeling

Development of Integrated Models

In Figure 2, an overview of the development of numerical modeling in urban wastewater management is given, starting with what is considered completed, showing what is currently under development and what will be the future challenges. The following distinguishes between offline models and online models.

- Offline models are used for the design of the system and the development of control strategies or decision support. They do not interact with the real processes running in the system.
- Online models interact with the processes in the system and are applied for online evaluation and prediction for choosing the best operation or control option. A beneficial side effect is that online simulation may also be used for fault detection in the measurements and malfunctions in the operation. Model-based predictive control with regard to the

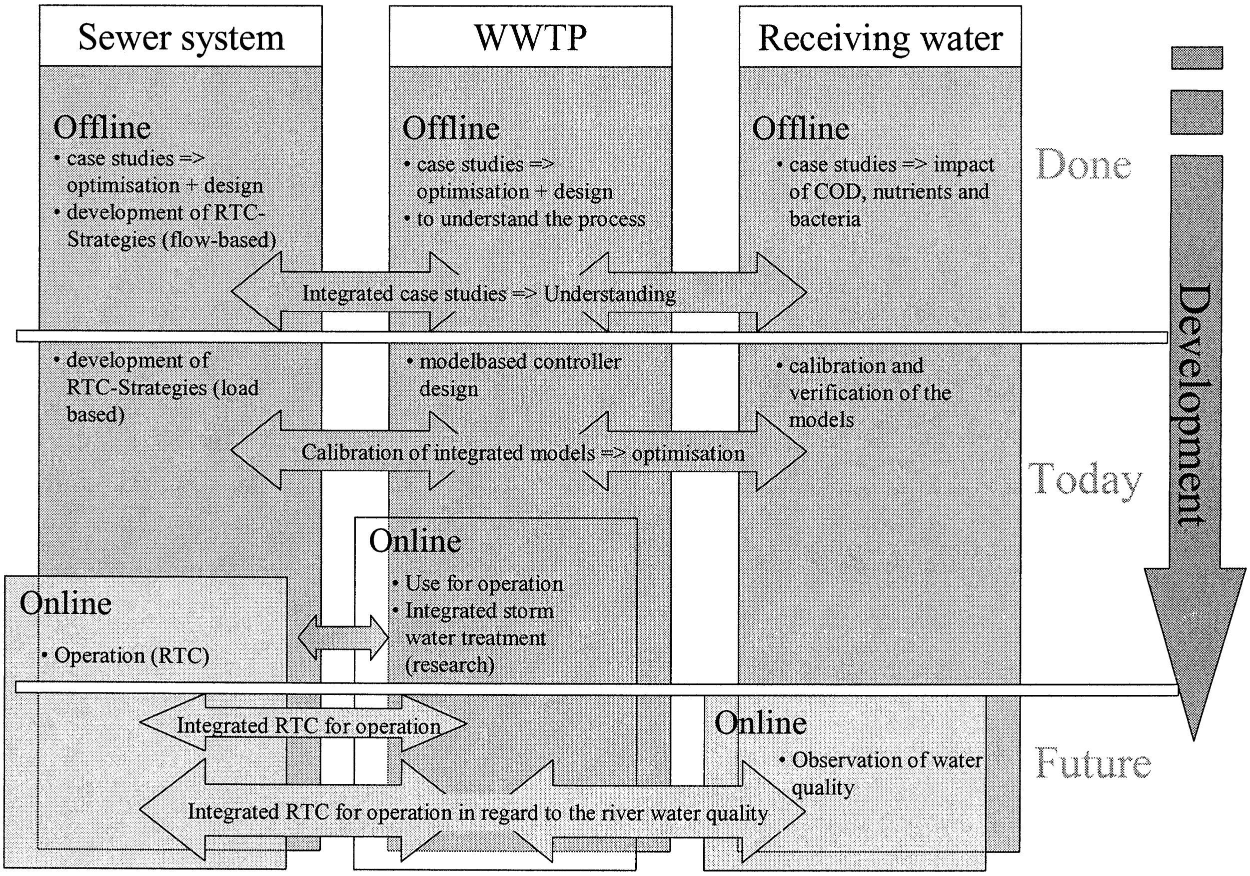

Figure 2. Development phases of the models and the way of integration (Seggelke 2002).

integrated systems operation is a future challenge where the goal is to make use of synergy potential originating from the interactions between the subsystems.

State-of-the-Art in Modeling the Wastewater System

In recent history, offline models were developed for the optimization of the individual wastewater subsystems: sewer, WWTP, and receiving water. The models were coupled for integrating subsystems in case studies to understand the behavior of the total system. Typically, the models of the individual subsystems were run in a sequential mode; that is, the interfaces were not treated interactively, but the results of the ''upstream'' systems model were used as input data in the ''downstream'' systems model. The current status of these models is explained in Table 1. Problems to be solved are the appropriate conversion of state variables at the models interfaces (e.g., Rauch and others 1998) and the consideration of the full short-term transport dynamics in the sewer system and at the interfaces (Krebs and Rauch 2000). Another challenge will be the coupling of physical and chemical impacts with the ecological status of the receiving water. Further information on the simulation modes, sequential or parallel, and the associated limitations and difficulties, respectively, can be found in Rauch and others (2002a) and Erbe and others (2002).

Integrated Offline Models for System and Control Strategy Development

Today's research projects deal with the calibration and verification of the integrated offline models with measurement data. This is an important prerequisite for the optimization of control strategies in the real system, because this requires realistic absolute results as opposed to relative comparisons for choosing the best systems development approach.

In past years, various case studies in research and even in practice were carried out to understand the interactions between the subsystems. In Erbe and others (2002), an overview is given of a number of integrated modeling studies and their features. Despite this

Table 1. Present status of models of the wastewater subsystems

Model	Sewer system	WWTP	Receiving water
State	• Modeling of rain runoff and hydrodynamics successful • First approaches to describe the biological sewer processes (e.g., Huisman 2001)	• Many experiences in using models (e.g., ASM), calibrated and verified for longer periods (exact knowledge of the plant necessary)	• Various models, standardized IWA model, extremely difficult to calibrate
Difficulties to develop	• Load-based models including sedimentation and erosion • Modeling of the processes in the CSO and retention structure	• Modeling of hydraulic problems, e.g., oxidation ditch • Description of settling processes	• Measurement and calibration • Description of the input from agriculture • Link between biochemical status with the ecological status

activity, there are still unsolved problems in making the integrated models more reliable. A key problem is that measurement data that allow the calibration and verification of the rather complex models, such as testing real-time control (RTC) strategies for the application in practice, are still scarce and costly (Vanrolleghem and others 1999). Furthermore, error propagation and uncertainty analysis of the process sequence (from rainfall to receiving water impact) is only rarely investigated.

For integrated control purposes, the models describing the processes in the subsystems must be run in parallel. To decide on control actions, various control options must be simulated and evaluated. Therefore, the models developed so far are simplified and especially adapted for consistent data exchange at the interfaces (see, e.g., Schütze 1998).

Development of Integrated Online Models for Operation

Online modeling of processes in the sewer system and in the WWTP individually is currently applied in practice and remains an ongoing field of development. The future perspective includes the integration of the online models for RTC of the sewer system and WWTP to minimize the total emission in relation to river water quality. The development of the online connection of the models with the real processes facilitates model-based predictive control, which is an important tool for the integrated operation of the processes in the WWTP and the sewer system. It would support the systems operator in following the water-quality-based approach. In other words, online connected models improve the case-dependent performance of the wastewater system as a whole, resulting in minimized impacts on the receiving water quality.

The following section introduces a research project carried out at the University of Hanover, where an online WWTP model (activated sludge technology) was coupled with a sewer model for integrated control. The aim is to make optimal use of the WWTP capacity during storm events to increase the combined water inflow to the WWTP beyond the double dry-weather peak flow typically allowed, while still meeting the effluent standards. The case-dependent full treatment capacity is continuously estimated by an online observer model that is frequently compared with measurement data from online sensors. A model-based adaptive prediction tool is implemented to predict the WWTP performance for different control strategies and under different loading scenarios caused by varying the inflow to the WWTP. For the latter purpose, the WWTP model, ASM2d implemented in Simba® (Institute for Automation and Communication ifak, Magdeburg, Germany), is coupled with the sewer model Kosim (Institute for Technical and Scientific Hydrology itwh GmbH, Hannover, Germany). In order to assess various operation scenarios from a water-quality perspective, two criteria were applied in the receiving water: the ammonia and the oxygen concentration in the receiving water. With regard to the ammonia concentration, the near field of the discharge point is decisive and thus simple local mixing was computed. The identification of the minimum oxygen concentration is required here to model the river for several kilometers downstream. A tanks-in-series approach including a simplified reaction model was applied in order to save computation time (for details see Seggelke 2002).

Figure 3 shows the structure of the adaptive predictive approach as it was installed at the WWTP (Seggelke and Rosenwinkel 2002). The WWTP prognosis model receives information on concentrations and loads in the inflow from simulations with KOSIM

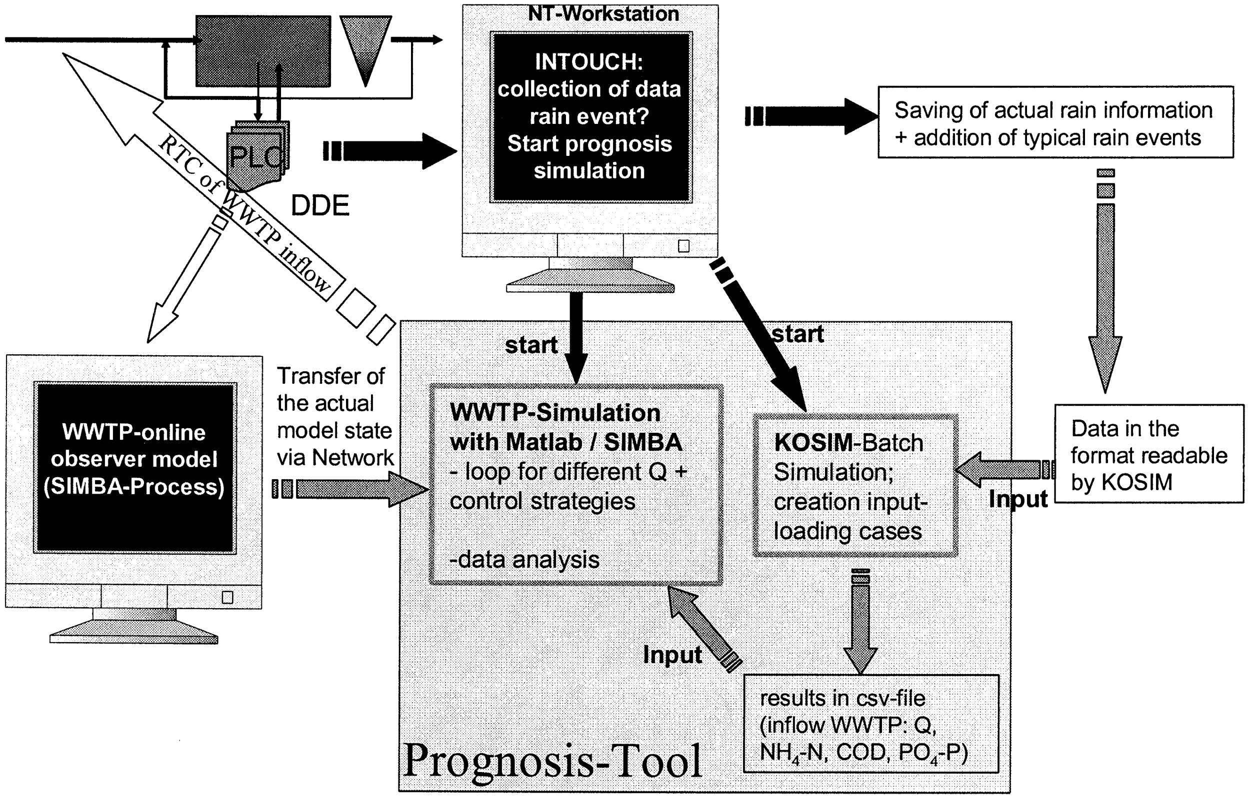

Figure 3. Online-simulation system with model-based prediction (Seggelke 2002). PLC, programmable logical controller; DDE, dynamic data exchange.

and information on actual state of the biological process from the online observer model. Based on these inputs, the WWTP effluent quality can be predicted continuously for various loading scenarios, allowing for estimates of the maximum possible inflow and choosing the appropriate control strategy for the WWTP operation in case of combined water inflow. Details on the model, the prerequisites for the online implementation, including fractionation and influent generation, and the WWTP control strategies can be found in Seggelke and Rosenwinkel (2002).

The tool was applied in simulations and compared to scenarios with various static rules for WWTP inflow under wet-weather conditions (Seggelke 2002). The findings may be summarized as follows:

- From the point of view of the receiving water quality, no optimal constant inflow rate to the WWTP can be specified. The optimal inflow rate varies depending on the event, i.e., the rain intensity and duration, on the actual base flow in the receiving water, and on the initial conditions in the system.
- Depending on the phase of the event, the WWTP exhibits significantly different loading capacities. During the initial phase of the event, when the concentrated dry-weather wastewater is washed out from the sewer system and the primary clarifier (Krebs and others 1999), nitrification is the limiting process and does not allow a high WWTP loading. Later, in the dilution phase, the free capacity is typically significantly higher before it is reduced again during the emptying of the combined water storage.
- Because the optimal WWTP inflow rate with regard to receiving water quality depends on both the event's characteristics and the event's dynamics, it could be shown that there is optimization potential for the predictive and integrated control outlined above. The tool has been developed and applied within a case study; however, up until now it has not been built into the control system of the WWTP. One of the major problems is the accuracy and reliability of online measurement devices, because they provide important input information. Presently, the investment costs for the implementation of such systems are high and the prerequisites to run them are demanding. Applications in practice will allow for establishing the cost–benefit relationship and evaluating possibilities to simplify the system.

Source Control and Public Participation

In this section, we are interested in discussing the second integration theme of ''technical systems and the public'' as introduced earlier. Discussions around the importance of the role of the public and local knowledge in urban drainage planning and management, and in particular pollution prevention, have gained significant momentum over the last decade (see, e.g., Maksimovic and Tejada-Guilbert 2001, Johnson and others 2002, Robertson and McGee 2003). This also reflects the growing recognition of the need to move away from a sole reliance on end-of-pipe technological responses towards the integrating concept of source control and the role of the public as an integral component of the urban drainage system for addressing contemporary sustainability issues (Lundqvist and others 2001).

For this paper, we view source control as processes designed to manage the sustainability issues associated with urban stormwater runoff and pollution at their origin. Therefore, source control necessarily acknowledges the interaction between society and the physical environment. Urban stormwater source control management techniques are often divided into structural and nonstructural techniques (see, e.g., Brown 1998, NSWEPA 1998, Taylor and Wong 2002) and broadly include:

- *Structural Source Control*: techniques that aim to reduce the quantity and improve the quality of urban stormwater at or near its source by using infrastructure and/or natural physical resources, and
- *Nonstructural Source Control*: approaches that aim to change social expectations, practices, and behaviors for reducing both the quantity of urban stormwater runoff and generation of pollutant loads entering urban drainage systems.

Source Control Techniques in Urban Storm Drainage Management

Source control research and practice to date largely reside in the structural domain. This focus mostly incorporates improved urban design practices through the process of retrofitting existing urban storm drainage systems. This includes various structural source control techniques such as rainwater and urban drainage harvesting and reuse techniques (see, e.g., Coombes and others 2002, Herrmann and Schmida 2000, Nolde 2000), physical retention and infiltration practices (see, e.g., Matuzic and others 2001), and water-quality management techniques such as treatment wetlands and bioretention systems (see, e.g., Lloyd and others 2001, Walker and Hurl 2002). These types of interventions are concerned with facilitating both sustainable urban water use and protecting and restoring the sustainability of receiving urban aquatic environments.

However, implementation of structural source controls alone is simply not sufficient for addressing the ongoing and often escalating issue of pollution generation caused through household and catchment land-use practices and behaviors. The importance of nonstructural source controls is further highlighted when considering the lack of suitable conditions for implementation of structural management techniques in established urban drainage environments (WEF 1998). Therefore, nonstructural source controls are required for addressing contemporary urban drainage issues, which increases the scope and sophistication of the management strategy by integrating the social and technical interfaces of contemporary sustainability problems.

Nonstructural source controls are interventions concerned with addressing the social dimension of catchment land uses. This can include governmental administration activities, such as street cleaning, waste collection, and land-use planning regulations, and local community practices and behaviors, such as littering, household property maintenance activities, and vehicle usage (NSWEPA 1998, WEF 1998). As discussed by Brown (1998), Brown and Ryan (2001a), and Taylor and Wong (2002, 2003), nonstructural source controls can be grouped into intervention types based on land-use management practices, such as planning, regulative-, procedural-, educational-, and financial-offset initiatives. What appears to be common throughout these approaches is the need for varying levels of stakeholder collaboration and/or public participation as essential to pursuing effective sustainability outcomes.

By contrast to structural measures, the consistent application and research into nonstructural source control management interventions is far less developed and appears to be clouded with significant uncertainty, particularly in terms of outcome quantification (WEF 1998, Taylor and Wong 2002, 2003). In addition, as also highlighted by Marsalek and others (2001), there appears to be a lack of support for dedicated outcome and evaluation research into the implementation of government-sponsored nonstructural source controls, such as ''integrated urban stormwater planning'' and ''community education'' programs. Further, more complex interventions, such as the phasing out of dangerous and unwanted substances at the level of production and consumption within households and catchments that end up in urban water drainage systems, pose significant challenges for conceptualizing and implementing source control research efforts in the future. Given this, there is a distinct need for dedicated implementation and outcome research across different contexts to generally inform and advance the practice of integrated urban stormwater drainage (Kerr and Chung 2002, Brown 2003).

Public Participation and Source Control

Public participation and stakeholder engagement processes are increasingly being advocated at all levels of government as essential ingredients to pursuing sustainable urban water futures. Of particular note is the implementation of the European Water Framework Directive based on the philosophy of facilitating an ecosystem-based approach, which is anticipated to transform traditional planning and management dialogue by providing significant opportunity for stakeholder engagement and public participation (Kallis and Butler 2001, Gullstrand and others 2003). Public participation typically refers to the facilitation of various types of deliberative processes largely involving lay community members in active negotiation and debate in the public realm (Harding 1998, Chopyak and Levesque 2002), whereas stakeholder engagement typically refers to involvement of representatives from various established organizations. This includes community interest groups, nongovernment organizations, environmental associations, industry associations, and professional organizations (for explanation of further distinctions between public participation and stakeholder engagement processes, refer to Hendriks 2002).

Although seldom made explicit through research results, it is often understood that such processes are enablers for changing social expectations, practices, and behaviors through generating awareness and learning, as well as potentially increasing the level of political and local support for the implementation of innovative and more sustainable management approaches. Although there are a number of recognized typologies of public participation (see, e.g., Bishop and Davis 2002), for urban storm drainage it is considered here that public participation is best represented as a continuum of increasing political commitment towards community values driving the decision-making process, which is largely consistent with a governmental service provision perspective on participation.

The sustainability discourse further advocates the need for moving away from solely traditional top–down decision-making processes at the local level, such as those typical of urban drainage management, towards integrating bottom–up decision-making processes with public participation as the central component (Warburton 1998). Commentators on advancing more sustainable structural management techniques are also increasingly coming to the conclusion of the need for public participation in both planning processes and selection of management intervention techniques for pursuing sustainability (see, e.g., Burkhard and others 2000).

The idea follows that public participation can lead to positive changes in social practices and behaviors that impact on the sustainability of urban drainage environments and therefore is an enabler for realizing nonstructural source control (Brown and Ryan 2001b) and the transformation of existing frameworks that largely support the continual practice of unsustainable management practices (Lundqvist and others 2001).

Australian Case of Public Participation and Urban Stormwater Planning

Brown and Ryan (2001b) conducted evaluation research on the implementation of an integrated urban stormwater management program in Australia and found that the majority of attempts at bottom–up public participation largely resulted in processes that replicated the traditional top–down process (on the left side of the continuum; Figure 4). This research also revealed that these prevailing top-down participatory processes were biased in favor of structural end-of pipe outcomes over source control solutions. This is because the technical experts that dominated the process were conceptually bounded by the existing urban drainage system, resulting in path-dependent technological solutions.

However, Brown (2003) subsequently developed critical insights into the relatively smaller sample of urban catchment planning projects that were successful in facilitating participation processes more aligned with the bottom–up end of the continuum. These cases produced catchment plans that demonstrated higher levels of local political commitment to nonstructural and structural source control interventions than to traditional end-of-pipe techniques. This research revealed that the participating communities were not as constrained by the existing system as the traditional technical experts and naturally advocated integrated solutions, demonstrating thinking beyond ''technological fixes.''

The difficulties faced in achieving bottom–up public participation, such as in the Australian case, can be attributed to a number of issues related to the

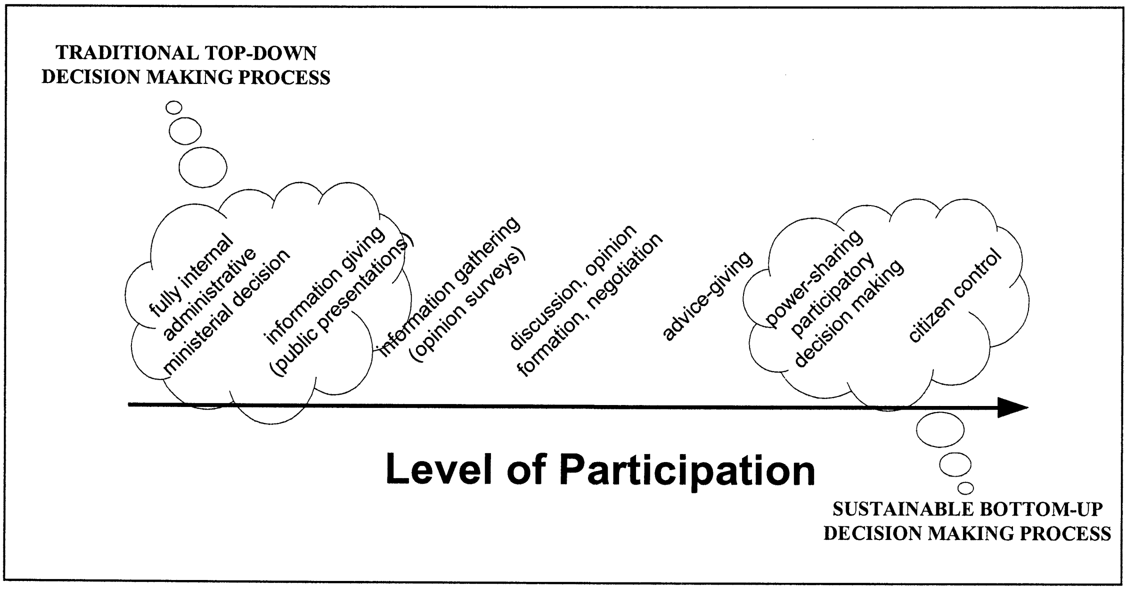

Figure 4. Public participation continuum (modified from Brown and Ryan 2001a).

inertia of existing professional and organizational practices. The main barriers identified to realizing effective bottom–up participation include (Brown and others 2001, McManus and Brown 2002, Brown 2003):

- *Participation methodologies used* were largely unsuitable for the target communities. For example, they involved narrowly scoped public meetings that were planned and programmed without consideration of community needs. That is, they were community information sessions rather than participation sessions. These attempts also did not recognize and cater to community characteristics such as diversity in language and culture and disabilities that hinder meaningful participation potential;
- *Existing capacities of communities to participate* were overestimated. Many community groups and individuals that were interested in participating felt they lacked the time and cost resources to meet a predetermined participation schedule. Many also believed they lacked the political and negotiation skills to effectively contribute to the outcome, also demonstrating a lack of community confidence;
- *Professional norms and practices* were not adequate for the administration of the planning processes. Overall, urban drainage engineers were assumed to be the appropriate professionals for administrating these processes on behalf of their municipality because of their history with urban drainage issues, even though this profession lacks community engagement expertise; and

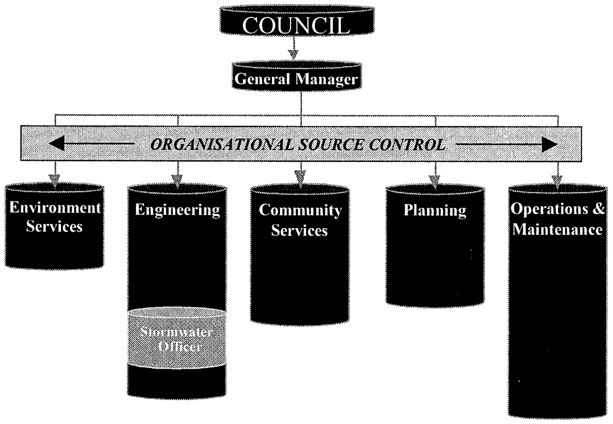

Figure 5. Functional silos of local land-use/municipal organizations (Brown 2003).

- *Organizational structures and norms* hindered the transfer of knowledge and experience between and from the various functional areas within the local organization (Figure 5) to communities. For example, road maintenance and street cleaning are usually conducted in the organizational silo of engineering, whereas habitat restoration and waste management are usually located in the environmental services silo. Although the knowledge of these organizational functional areas is essential for integrated urban drainage management, the structural organization division proved to be a major obstacle to participation. This is because communities wanted access to whole-of-organizational knowledge for decision-making, yet only one area (and often an individual engineering officer) of the municipal organization was responsible for the planning process and, therefore, the participation processes could not provide information considered adequate by communities.

Future Needs for Advancing Successful Public Participation and Source Control

To overcome these observed difficulties with enabling effective participative processes, as identified in the Australian case, future practice needs to explicitly acknowledge the inertia of existing professional and institutional norms and practices as cultural and technical obstacles (Fischer 1990, Brown 2003) for the realization of bottom–up public participation and nonstructural source control. Traditional ways of managing urban drainage problems are likely to prevail if communities are not directly empowered through capacity-building processes to participate in planning and decision-making. As also identified in Healey's (1997) research, effective community and local organizational capacity are necessary for bottom–up participation, which needs to be built and facilitated through transdisciplinary approaches. Although this area of research remains largely in its infancy in the field of urban storm drainage, research by Brown (2003) has shown that the following social attributes of urban catchments are important for enabling bottom–up participatory processes and overcoming existing inertia:

- *Local political support*: necessary for redistributing funding, promoting organizational change, facilitating broader community awareness, maintaining professional and organizational momentum for innovation, and focus on source control strategies through process empowerment;
- *Commitment to communities*: a disposition necessary for allowing local political support. This requires appropriate training and skill of local organizational staff and an appreciation of the power of shaping local social norms and behaviors for effectively addressing urban drainage problems;
- *Transdisciplinarity*: necessary for promoting a climate in which a range of expertise is valued including local, community, and indigenous knowledge. This is also important for addressing the professional inertia in the urban drainage industry and being a catalyst for developing innovative sustainable solutions; and
- *Institutional capacity*: necessary for strengthening the key relationships between all the players in the catchment and developing a common focus on the health of the aquatic environment. This capacity has the potential to create and shape existing decision-making frameworks that can create action and change to improve urban drainage management. In this section, we considered what source control is and how it relates to public participation. Current research suggests that best practice is limited in its ability to enable effective bottom–up public participation and nonstructural source control. This is due to both the inertia of existing practice and the escalating need for dedicated implementation research in this area of sustainable urban stormwater management. Overcoming this will require explicit attention to the social dimensions of urban catchments.

Problems of Integration

In the previous sections, methods and benefits of applying integrated approaches have been discussed. In order to complete the picture, some problems and possible shortcomings of integration also are addressed in the following. Central to this discussion is the principle of precaution.

A basic problem when dealing with the urban drainage system in a holistic way is the significant level of complexity of these systems. Although specific aspects can be described by means of deterministic cause–effect relations (Rauch and others 2002a), a substantial part of the system exhibits either random behavior, or the underlying processes are so complex that the causality cannot be sufficiently described. Either way, the result is that real system behavior can be only partly explained by deterministic models.

Integrated approaches, however, are inherently based on the idea of causality between pressure and impact. The key point is to minimize detrimental effects to both the environment and society by taking exactly those measures that most efficiently prevent adverse impacts. However, what should be done when the impacts cannot be identified, or if no clear cause–effect relation can be established? There are two fundamental ways to tackle the problem:

- The first one is to apply the precautionary principle, which can be essentially expressed as follows: if we do not know the consequences, we must enact decisions and measures to avoid and/or alleviate the pressure. In the case of urban drainage, the measure most often applied in terms of precaution is a detention basin to partly prevent CSO to the receiving waterway environment. However, this solution does not fulfill the fundamental principle of integration because the idea is to restrict emissions and not to improve the overall performance of the system.

- The second possible pathway is to accept the inability to describe the details of the systems and to focus only on those areas where a cause–effect relation can be established. The result is that the most visible and often important problems are tackled in a holistic fashion but numerous others remain without consideration. Therefore, there is a certain chance that measures determined to be optimal in the present integrated view on the system turn out to be suboptimal in reality, the reason being that the causal link was not established. This clearly illustrates that the application of integrated approaches in the management of urban drainage systems is inevitably connected with uncertainty in the outcome. Field studies to reduce this incertitude require huge investments. Thus, risk assessment procedures are advocated increasingly (e.g., Harremoës 2003) as a means for balanced decision making under uncertainty. However, it is because of these problems that the implementation of water-quality-based regulations is slow.

Conclusions

In the scientific community, an increasingly holistic view on the analysis, design, and operation of urban stormwater drainage systems is advocated. Starting with early efforts nearly two decades ago, the application of integrated approaches has recently gained particular momentum in both the physical and human system realms. This paper summarizes the status with respect to regulations, tools, methods, and possible perspectives.

Integration on the level of the technical system is applied by taking a holistic view on the operation of the system, consisting of the sewer system, the wastewater treatment, and the receiving water. For the implementation of management strategies, numerical tools are required to predict the behavior of the complete system under historical and future scenarios. Although such tools and methods exist, there appears to be a significant conservatism in the profession with respect to their application. Another problem is the high complexity of the system that prevents the establishment of clear cause–effect relations between the behavior of the technical system during wet weather and aquatic ecosystem impairments.

The second level of integration considers both the technical system and the socioeconomic implications. Current best practice is limited in its ability to enable effective bottom–up public participation and nonstructural source control. Research so far suggests that overcoming this obstacle requires significant attention to improving the organizational administration and capacities of existing and new professionals within the urban water management field.

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