# Modelling real-time control options on virtual sewer systems

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**Abstract:** The study presents a benchmarking methodology to assess the performance of sewer systems and to evaluate the performance of real-time control (RTC) strategies by model simulation. The methodology is presented as a general stepwise approach. Two virtual sewer systems were modelled under four climate conditions. Catchment A represents a small system with medium RTC potential, while catchment B represents a large system with large potential according to PASST guidelines. The rain data represented Oceanic, Continental, Alpine and Mediterranean situations. Annual precipitation data was used. Tests included operation without RTC, and with two classic RTC strategies, aiming at, respectively, equal filling of storage tanks (“average filling”), and aiming at avoiding spilling just upstream of the treatment plant (“WWTP load”). The results have shown that similar RTC strategies perform differently under various climatic conditions and in sewer systems. The presented benchmarking methodology can be used to test the impacts of various climate scenarios on sewer systems that suffer from the limitations of static design.

*Key words:* real-time control, RTC in sewer, mathematical modelling, simulation, virtual sewer catchment.

**Résumé :** Cette étude propose une méthodologie de référence pour évaluer le rendement des systèmes d’égout et des stratégies de contrôle en temps réel par simulation modélisée. La méthodologie est présentée sous forme d’une approche générale progressive. Deux systèmes d’égouts virtuels ont été modélisés pour quatre conditions climatiques. Le captage A représente un petit système présentant un potentiel moyen de contrôle en temps réel, alors que le captage B représente un grand système présentant un grand potentiel selon les lignes directrices PASST. Les données de précipitations représentent des environnements océaniques, continentaux, alpins et méditerranéens. Les données de précipitations annuelles ont été utilisées. Les essais comprenaient le fonctionnement sans contrôle en temps réel et avec deux stratégies classiques de contrôle en temps réel, visant respectivement le remplissage égal des réservoirs de stockage (« remplissage moyen ») et à éviter le déversement tout juste en amont de l’usine de traitement (« charge WWTP »). Les résultats ont montré que des stratégies similaires de contrôle en temps réel ont des rendements différents selon les conditions climatiques et les systèmes d’égouts. La méthodologie de référence présentée peut être utilisée pour analyser les impacts de divers scénarios climatiques sur les systèmes d’égouts qui subissent les limitations de la conception statique.

*Mots-clés :* contrôle en temps réel, contrôle en temps réel dans les égouts, modélisation mathématique, simulation, captage virtuel des égouts.

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## Introduction

The objectives of this work are the development and application of a stepwise methodology for evaluation of real-time control (RTC) alternatives for virtual sewer systems, in this study under varying climatic conditions. The presented simulations examine the potential of RTC to maintain or improve the performance of sewer systems designed according

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to “static” design rules on the basis of a design storm, but exposed to atypical loads or climates. It therefore permits to evaluate the adaptability of an RTC-augmented sewer system to deal with changing (climatic) conditions.

The work presented here is part of a larger project, CD4WC (Cost-effective development of urban wastewater systems for Water Framework Directive compliance, CD4WC 2006), and is thoroughly detailed in the project deliverable 6.1: “Real time control in the sewer system” (BIOMATH 2006).

## Background

A methodology to optimize the sewer system is the use of RTC. Its operation requires objectives that can be defined by mathematical formulae, and which in the present case (and usually in urban drainage systems) is the reduction of volume and (or) number of combined sewer overflows (CSOs) without (volumetric) extension of the existing system. It has been demonstrated that application of RTC allows large reduction of CSO volumes (Schilling et al. 1996). Other objectives may be the reduction of accidental spills, the attenuation of flooding or the reduction of energy costs.

A wastewater system is controlled in real time if process data, such as water levels, flows, pollutant concentrations, etc., are concurrently and continuously monitored in the system and this monitoring data is then used to manipulate actuators during the actual flow conditions. Actuators are usually pumps, sluice gates and movable weirs that allow control of flow through them. The reason why RTC can improve the operation stems from the fact that parts of the urban wastewater systems are historically designed according to static design rules while the whole system nevertheless is operated under dynamic loading conditions.

### RTC in sewers — overview

The first RTC prototype for sewer systems was implemented at the end of the 1960s in Minneapolis-St. Paul (United States) and in the following years a few other cities had implemented RTCs as well (e.g., Cleveland, Lima, and Seattle). At the same time, other North American and a number of European cities (e.g., Bremen in Germany) started feasibility studies on RTC. The main objectives of nearly all studies were the reduction of the number of CSOs. Other objectives were the prevention of urban flooding and the minimization of operation and maintenance costs. The little progress in the early 1980s in RTC had shifted at the end of the decade and at the beginning of the 1990s, as new developments became possible thanks to the beginning revolution of the microprocessors (Schilling 1989).

A large number of publications show the extent of the research that has been carried out in the field of RTC for sewers; with a number of studies that focus on the theoretical issues of RTC (Rauch and Harremoës 1999; Schütze et al. 2002; Vanrolleghem et al. 2005) while others present real life experiments (Harremoës et al. 1994; Petruck et al. 1998; Pleau et al. 2005; Schilling et al. 1996). The literature distinguishes between three different types of RTC: volume-based RTC, pollution-based RTC (PBRTC), and water-quality-based (immission) RTC (WQBRTC). Further classification looks at the method of how the underlying control strategies are represented and developed; on the one hand off-line developed RTC strategies (the development and definition of the control strategy is completed prior to its implementation) and on the other hand on-line developed RTC strategies (the control strategy is determined by setting up a simulation model that is run on-line to make the decisions on how and where to act) (Pleau et al. 2005; Rauch and Harremoës 1999; Schütze et al. 2002; Schütze et al. 2004).

Most of the projects realized up to now were focusing on wastewater volumes only (volume-based RTC). In most cases, the impacts of CSOs were assessed using total discharge volume; the control strategy was designed to minimize the volume of spilled wastewater (Pleau et al. 2001). None of the earlier projects had considered the performance of treatment plants or effluent quality. However, besides these “traditional” approaches, some projects also aimed to equalize the inflow into the wastewater treatment plant (Schütze et al. 2002).

The increasing general interest of the scientific community in the field is shown by the appearance of working groups under larger international associations (Andrieu and Chocat 2004). One example is The Group on Real Time Control of Urban Drainage Systems (RTCUDS, a joint group of IAHR and IWA) and another is the technical board on Urban Drainage (under the German DWA).

### Objectives

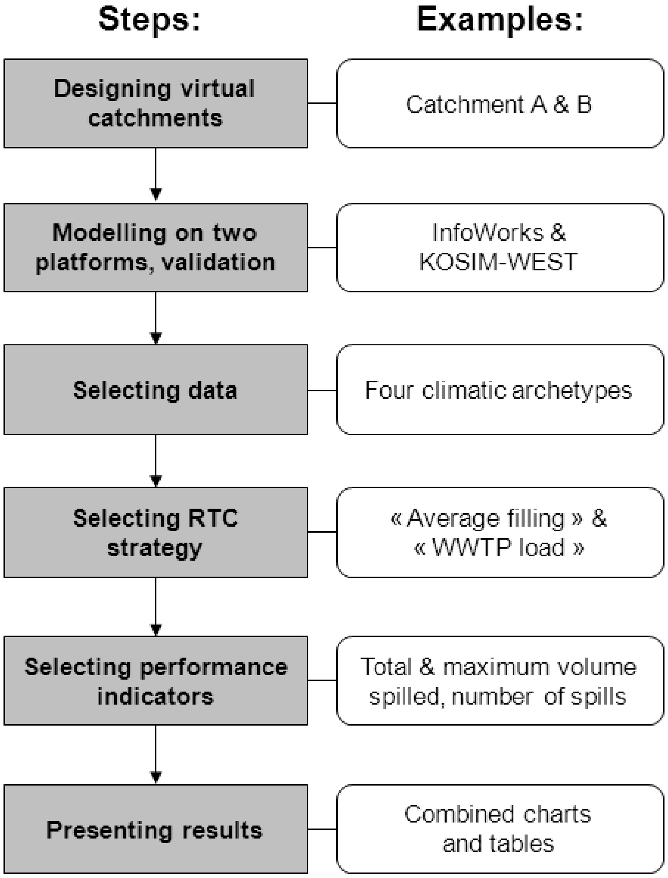
Since most actual sewer systems are developed according to static loading design rules, application of RTC in general can be expected to improve their performance. In addition, climate change makes it necessary to adapt sewer systems with a life expectancy of tens of years to the new loading situations that are developing (Butler et al. 2007). These new loading conditions are typically not considered in the physical design and little in the actual RTC strategy. To test and analyze a range of existing systems with dynamic loads and various RTC strategies, one must develop a benchmarking system that establishes the frames of such model simulation studies. This work attempts to present such a system.

## Methods and models

### Benchmarking methodology

This article introduces a benchmarking methodology, a general stepwise approach based on model simulations to analyse the effects of climate and the so-called RTC potential on sewer system performance. Figure 1 illustrates the structure of the methodology. The steps followed are designing the virtual catchments (later in this work these will be catchment A and B), dual platform modelling and validation (here InfoWorks, Wallingford Software Ltd, Wallingford, UK and WEST, MOSTforWATER N.V., Kortrijk, Belgium), selecting data with appropriate features (quality, length, etc, year long actual series from typical regions or climate-change scenarios), selecting RTC strategies (here “average filling” and “WWTP load”), selecting performance indicators, and presenting appropriate results. The aspects and steps of the methodology form the backbone of this article.

**Fig. 1.** Illustration of the presented framework for a benchmarking methodology, as a general stepwise approach.



## Application of the benchmarking methodology

Within this structure, impacts of climate scenarios on performance of RTC strategies are compared with each other. The comparisons are based on yearly sums of number of spills, total spilled volume, and maximum spilled volume in a single CSO event. More information can be found in CD4WC (2006). Alternative approaches for performance evaluation may consider pollutant concentrations or other sewer flow related features, but these are not discussed here.

Two virtual catchment models, called catchment A and catchment B, were developed to provide the test field for the analyses. Tests were performed first neglecting RTC possibilities, and then with the application of two different RTC strategies on both catchments. Four climatic archetypes were used in the cases representing Oceanic, Continental, Alpine, and Mediterranean climates. In fact these four climate scenarios created from existing climates in Europe are applied to an existing sewer system (located in and therefore designed according to Oceanic climate) that is subject to new climate conditions. The performance alteration that is the result of these new conditions is evaluated. When the performance remains reasonable despite these different climate conditions, one can say the RTC strategy is successful in augmenting the adaptability of the existing sewer system.

## The virtual catchments

Table 1 shows the global characteristics of the two virtual catchments. These were selected according to the most important criteria of the PASST methodology (Schütze et al. 2002; Schütze et al. 2004) to design a catchment with medium potential (catchment A), and another one with high potential (catchment B) for application of RTC. The characteristics specified by the PASST methodology (referred to hereafter as the PASST guidelines) are climate-independent, general features. These mainly regard the sewer catchment features, like its size, population and slope, the number of collectors and storage possibilities, like their total volume and distribution.

The further details of the catchments, which are not specified by these general guidelines, were compiled according to Flemish (Belgium) design rules. Such details include the capacity of all throttle structures, diameter of conduits, capacity and operation of pumps, etc. This way, the catchments fulfil primarily some general criteria (defined in the PASST guidelines), and secondary some specific criteria (Flemish guidelines), but only where the primary criteria do not provide enough information. The catchments are considered to be realistic; they fulfil all design regulations and guidelines in force in Flanders.

Figure 2 shows the layout of the two virtual catchments. Catchment A is basically divided into two parts at node 4, which is the inlet to the WWTP. The left sector is connected to the WWTP via a pumping station's rising main between nodes 3 and 4, and has a storage facility connected to node 3. This is the first controlled feature of catchment A. There are no CSOs besides the one at the storage structure in this sector. The right sector is connected to the WWTP via the conduit between nodes 11 and 4. This branch may be controlled by means of the sluice gate adjacent to the storage facility at node 11. This sector features three CSOs, one at the storage structure, and two others at nodes 13 and 16.

Catchment B has three main sectors, which again join at node 4, the inlet to the WWTP. The left sector contains a loop (nodes 2, 3, 6, and 7), and two storage structures at 2 and 3. There is an additional CSO at node 8 (marked R12). The only control option in this sector is the rising main of the pumping station at node 3, connecting this sector to the WWTP between nodes 3 and 4. The middle sector is smaller than the two others, has one storage structure at node 25, and an additional CSO at node 19 (marked R10). The only structure to control here is the sluice gate below the storage structure. The right sector has two storage structures at nodes 11 and 27 and four additional CSOs at nodes 10, 13, 16, and 26. Principally the two rising mains and the sluice gate can be controlled in this sector. The controlled structures and their features are further described below.

## Dual platform modelling

The following step in the methodology (Fig. 1) is the dual platform modelling. First on a hydraulically more accurate platform to get a good basis for calibration of the second stage, a more simplified approach in hydraulic terms, that would allow to simulate long time series and pollutant concentrations with an acceptable simulation time (Meirlaen et al. 2001; Vaes et al. 2002). Please note that the same catchment model was implemented on two different modelling platforms for two different purposes ((1) gaining acceptable hydraulic accuracy and (2) allowing long simulation periods

**Table 1.** Characteristics of the two virtual catchments A and B.

| Characteristic | Catchment A (Fig. 2 upper scheme) | Catchment B (Fig. 2 lower scheme) |
|---|---|---|
| Catchment area (length of main collector) | 3 km | 10 km |
| Number of existing control devices (e.g., pumps, slides, weirs) | 2 (1 pump, 1 gate) | 5 (3 pumps, 2 gates) |
| Slope of trunk sewers | 0.4% | 0.1% |
| Loops in the sewer system | 0 | 1 |
| Number of existing storage tanks (tanks and storage pipes) | 2 | 5 |
| Number of discharge devices | 5 | 11 |
| Total storage volume (tanks and storage pipes) | 3000 $m^3$ | 50 000 $m^3$ |
| Specific storage volume, including in-line storage (related to impervious area in subcatchments) | 30 $m^3$/ha | 50 $m^3$/ha |
| Number of collectors to the WWTP | 2 | 3 |
| Impervious area | 100 ha | 1 000 ha |
| Population equivalent | 30 000 PE | 300 000 PE |

and high computing speed). The two implementations are representing the same reality, they only differ in their detail, accuracy and, most importantly, calculation times.

The virtual catchments were therefore developed first on the InfoWorks platform (the standard hydraulic platform used in the project, see below), to provide the WEST version of the models with data for validation (WEST is the platform used in the project to run the simplified model, see below). The InfoWorks version of the model is run with a short simulation time, and is more realistic in terms of flow features than the WEST version. The models implemented in the WEST platform are then validated against the results of flow series created in InfoWorks for a short simulation time (0.5 day, see Fig. 3). This quasi calibration and validation allows carrying out year-long simulations, including simulation of pollutant components, on the validated WEST model. This kind of long-term simulation would practically be difficult to perform using the InfoWorks platform, since its fully hydraulic approach inherently requires larger computing time and capacity. Please note that pollutant concentrations may be considered in the control strategies, but are not discussed in this work.

InfoWorks is a modelling system for the management of sewer network models that features the numeric solution of the Saint-Venant equations (dynamic 1-D hydraulic simulation) amongst other features. Thereby it models sewer flow more accurately than a WEST model. Due to the implemented hydraulic concepts in InfoWorks simulation of long time series requires long simulation times, which would be limiting in the present approach. Simulation time would increase even more if interacting pollutant concentrations would also be included (however these are not discussed in the present study).

The WEST modelling and simulation platform (Vanhooren et al. 2003) allows one to construct models and conduct virtual experiments (e.g., simulations) on any kind of system that can be represented by differential algebraic equations. In addition to the extensive wastewater treatment plant (WWTP) modelbase included in the general WEST software distributions, other custom features are implemented. Most important in this work is the implementation of a hydrological model for surface runoff and sewer transport (hereafter referred to as KOSIM-WEST), based on the widely used KOSIM modelling system (ITWH 1995). The KOSIM model has been developed and extended by several researchers (Durchschlag 1989; Kollatsch 1995; Paulsen 1986) and implemented in the WEST modelbase by Meirlaen (2002) and Solvi (2007).

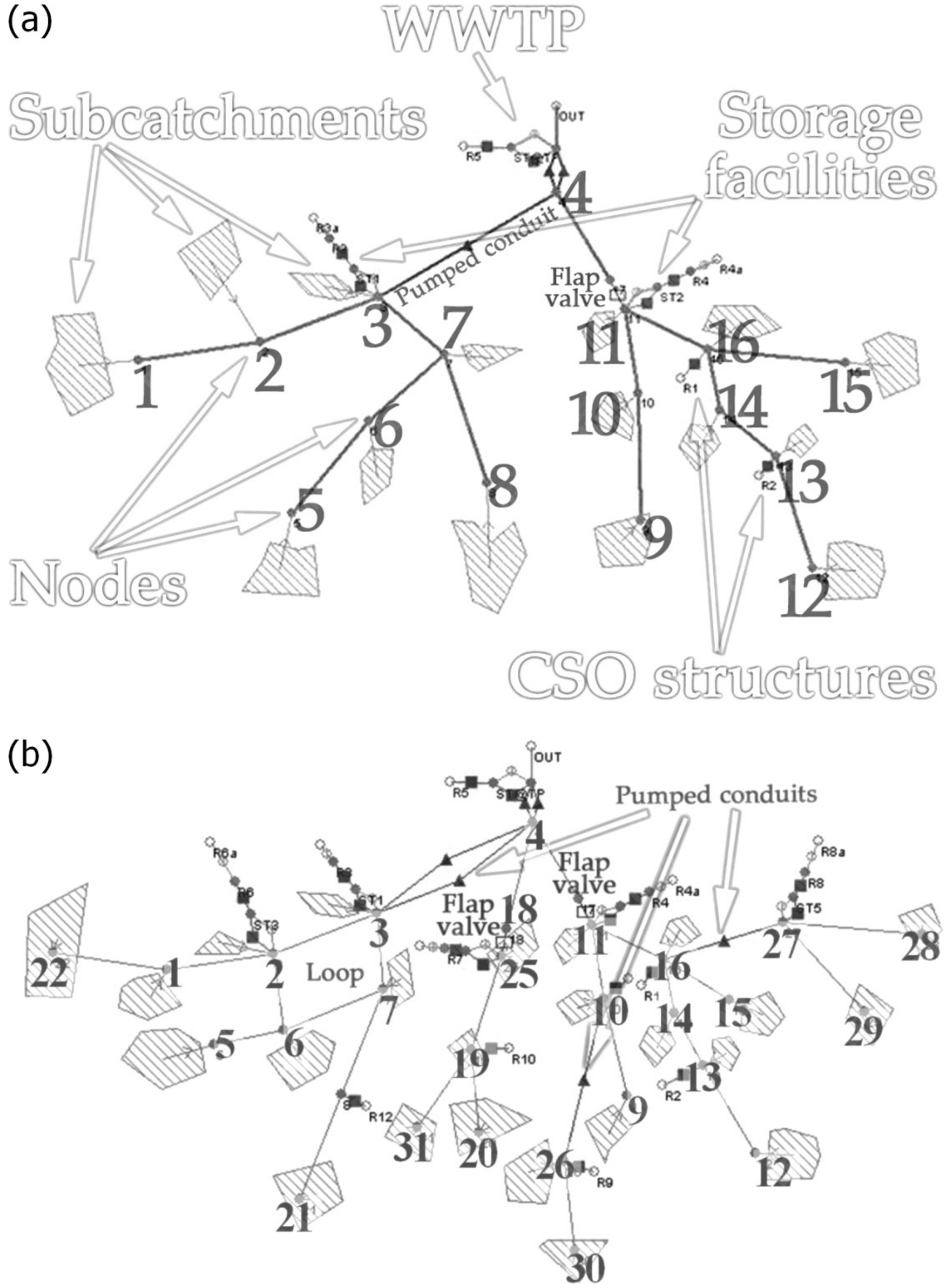
The catchment model in KOSIM-WEST, which provides the subcatchment components of the virtual catchments A and B, includes dry weather flow (DWF) generation and runoff calculation through wetting, depression, infiltration, and evaporation losses. The transport of the wastewater in the collectors is modelled following the method of linear reservoir cascades. This method is based on the Kalinin-Miljukov method, also known as tanks-in-series, where conduits are described by their characteristic length and the linear reservoir constant, usually noted as $L_c$ and $k$. A conceptual backflow model has been developed to give the possibility to account for backwater effects (Solvi 2007; Solvi et al. 2005). This tanks-in-series type model requires the preliminary definition of flow directions in the conduits, which has to be considered when modelling flow-loops in the sewer system. The additional submodels implemented from KOSIM besides the subcatchment model are described in detail in other works as well (Meirlaen 2002; Solvi 2007; Solvi et al. 2005).

## Model validation

Two datasets were used for calibration. These were the 2 year and 5 year return period formerly standard design storms in Flanders, Belgium. The design storms (or composite storms) were compiled on a multiple year time series of 10 min registered precipitation measured at Ukkel (near Brussels) following a statistical (intensity-duration-frequency or IDF) analysis. This is the standard procedure for designing combined sewage networks in Flanders. Figure 3 shows the graphical representation of the storms.

Simulated flows resulting from both model platforms at selected points of the catchments were compared, and runoff parameters of the subcatchment modules of the KOSIM-WEST model were adjusted to match those from the InfoWorks simulations. Integrated sewer volumes and maximum flows were compared at locations downstream of the subcatchment modules (at nodes 1, 2, etc. on Fig. 2). The parameters of each subcatchment are set similarly for all tests

**Fig. 2.** Schematic overview of catchment A (above) and B (below) in InfoWorks.



(four climates, two RTC strategies), and therefore it is not possible to reach a perfect match at validation for all cases. Validation primarily aimed at matching peaks (maximum flows) and total (integrated) volumes, and is understood as a "compromise" setup. Figure 4 shows an example of the result of two fitting simulations on the two platforms after validation. Other components (e.g., flow in conduits or storage fills) of the catchment models are not validated. In principle this is not necessary, because parameters used in the KOSIM-WEST (a tanks-in-series) model are already based on characteristics of the InfoWorks model, hence there exists a preliminary validation by definition of this model. On the other hand, validation has a much higher quality if it covers the (presently not considered, see above) network elements as well. This procedure would require an investment of efforts that were not available in the present case.

## Selecting data

Following the stepwise procedure illustrated on Fig. 1, the next step implies the data selection and preparation. Four climatic archetypes were applied to both catchments. The data were recorded at various locations in Europe, each of them describing typical and common climatic regions. In this way data from Palermo (Italy) describe the present Mediterranean climate, those from Brussels (Belgium) describe Oceanic climate, those from Dresden (Germany) describe Continental climate, and those from Innsbruck (Austria) describe Alpine climate in the study. These cli-

**Fig. 3.** Flemish (Belgium) composite design storms with (*a*) 2 years return period and (*b*) 5 years return period.

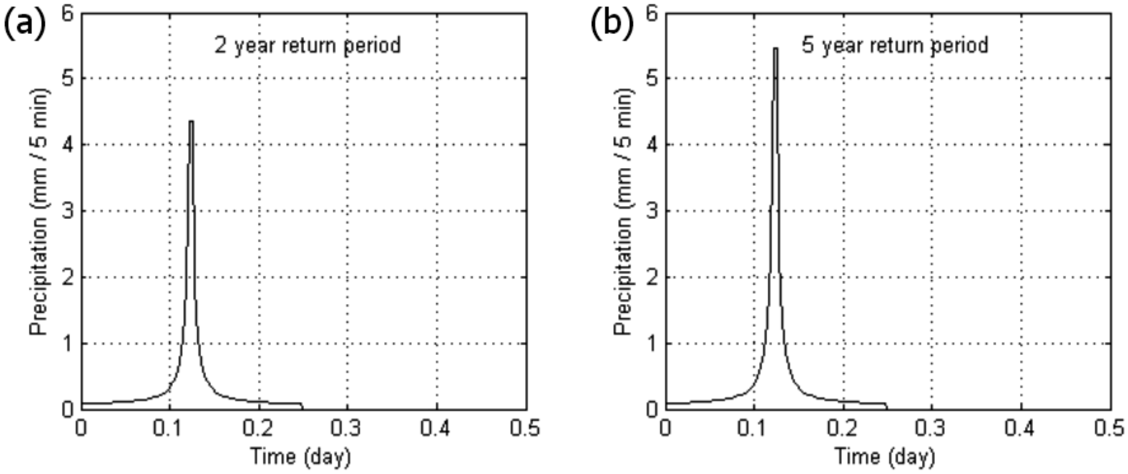
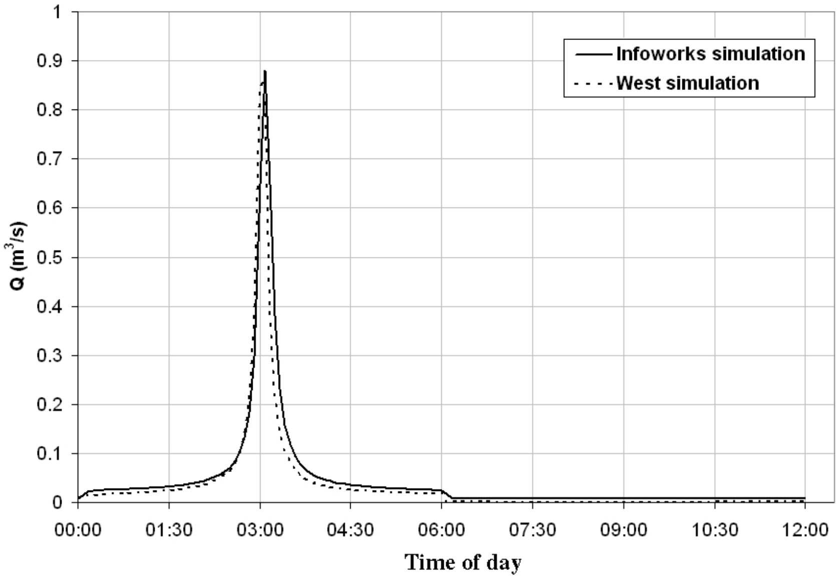


**Fig. 4.** Validation example, simulation results from KOSIM-WEST and InfoWorks (catchment A, subcatchment 1 outflow, 2 year return period design storm).



mates may be the climates the two virtual catchments are subjected to in the years to come.

Each data series has 5 min resolution, is 1 year long, and simulations were also carried out for the same period. Figure 5 shows plots of the four rain series. Please note that the unit of the data are mm/(5 min) on the figures. The total annual volumes of precipitation are obviously different in the four cases (see Table 2).

Each single series is applied to all subcatchments simultaneously during the simulations (for example to subcatchments 1, 2, 3, 5, 6, 7, etc, these are marked as hatched polygons on Fig. 2).

Besides the precipitation data, base flow is also modelled. The magnitude of this is calculated from the given total population equivalent (PE) values, that are distributed among the single subcatchments. A constant base flow is used (calculated as per capita flow multiplied by PE connected in the subcatchment), without any diurnal variation. The PE values used in this study are given in the PASST guidelines, see Table 1.

The presented work does not consider actual climate change scenarios. However, the simulation of atypical precipitation on a catchment helps in the understanding of how it functions in a shifted climate. This way the issue of climate change is addressed indirectly here. Recent works provide further guidelines on such studies (Butler et al. 2007).

## Selecting the control strategy

A control algorithm is a mathematical formulation establishing a relation between the manipulated variable (e.g., capacity of a pump or opening of a sluice gate) and the measured variable (e.g., the filling degrees). Following the classification in the Background section of this work, the present study considers the volume-based RTC and is an off-line strategy; PBRTC and WQBRTC are not discussed. The calculations for both strategies tested in this study are based on the filling degree (the ratio of actual volume to maximum volume, which may result in a minimum 0% to a maximum 100%) of storage structures in the catchments (not considering storage in pipes). This parameter is inter-

**Fig. 5.** Climatic archetypes and locations (values in mm/5 min).

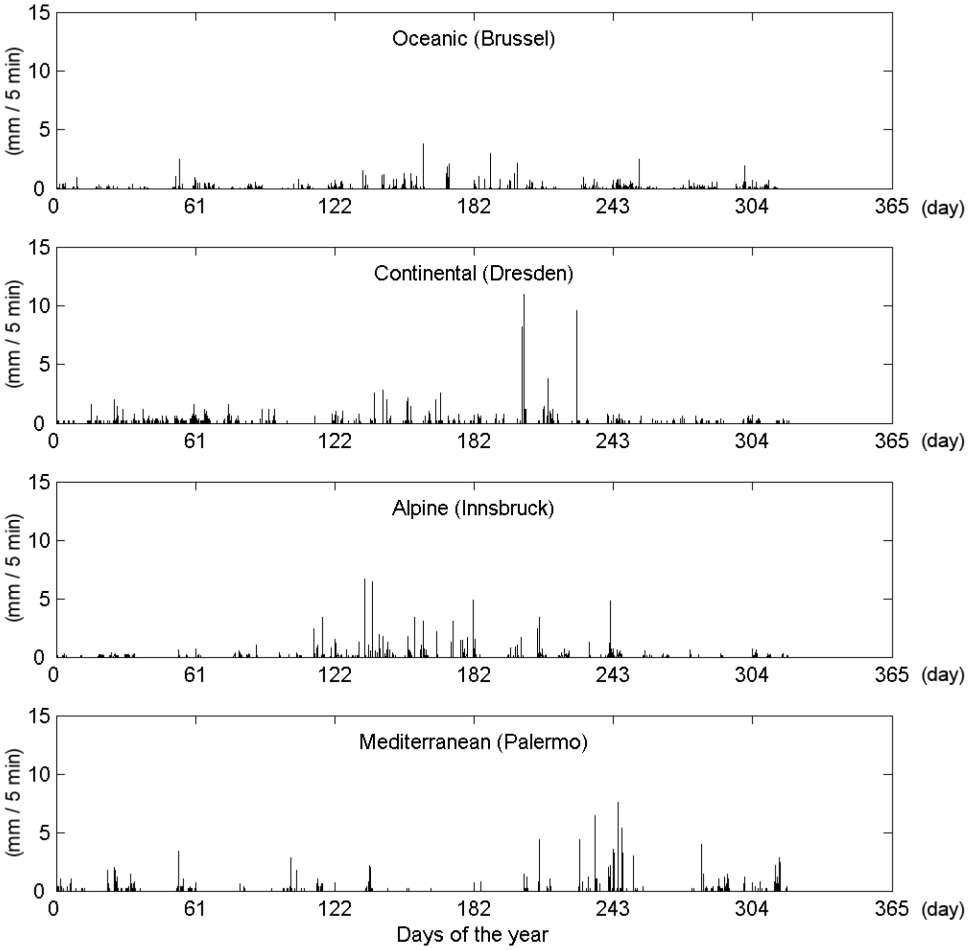


**Table 2.** The years and corresponding precipitation at the locations (climates) considered in the study.

| | | Precipitation (mm) | |
|---|---|---|---|
| Location | Year | Used in present study | Mean annual |
| Brussel (Oceanic) | 1982 | 801 | 825* |
| Dresden (Continental) | 2000 | 1015 | N/A* |
| Innsbruck (Alpine) | 2003 | 1154 | 548* |
| Palermo (Mediterranean) | 1996 | 809 | 609* |

*uk.weather.com (2007).

preted only on storage structures, not on conduits. Manipulated variables are openings of sluice gates and capacities of pumps (assuming frequency steered pumps, on and off levels are not manipulated in this study).

Further following the strategy summarized on Fig. 1, RTC strategies are to be selected. But first, simulations were performed with the non-controlled, fixed setup of both catchments (referred to as “no control”). This means that of all controllable features, such as capacities of pumps and opening of sluice gates, were kept constant during the simulation. The results of this simulation serve as reference in the following. It has to be noted that the values used for this fixed setting case are also indirectly optimized, as they form part of the design details that are determined according to the Flemish (Belgium) design rules.

Two typical, volume-based control strategies were selected (Butler et al. 2007; Schütze et al. 2002; Weyand 2002) and adapted to illustrate the benchmarking methodology followed in the study (Fig. 1). The strategies aim at

(1) reaching an equal filling degree of the storage tanks (referred to as “average filling”), or

(2) avoiding spilling at the most downstream collection point (“WWTP load”).

In general, the objectives of the strategies are expected to diminish the volume of CSOs, as in the case of Quebec City (Pleau et al. 2001), one of the best known large-scale application of volume-based RTC. The controllers include lowest and highest output limits (e.g., minimum and maximum capacity of a controlled pump, or minimum and maximum opening of a sluice gate), and a linear scaling factor to multiply the input variable when calculating the output variable of the control algorithm. Table 3 summarizes the algorithms in mathematical language.

The first strategy (average filling) compares individual filling degrees of controlled structures to the arithmetic mean filling degree of several structures. The controlled variable is then adjusted according to the deviation from the arithmetic mean. This strategy represents an economic principle from the investment point of view: if all storage facili-

**Table 3.** Mathematical models for storm tanks used in the KOSIM-WEST simulations.

| | General parameters (given, and constant during calculation) |
|---|---|
| dmax | maximum depth in tank (m) |
| q1 | pump 1 capacity ($m^3$/d) |
| q2 ($m^3$/d) | pump 2 capacity ($m^3$/d) |
| Hgate | maximum gate opening (m) |
| on1 | pump 1 turn on level (m) |
| on2 | pump 2 turn on level (m) |
| General variables (calculated run-time) | |
| d | Actual depth of water in tank (m) |
| ActFD | Actual filling degree = d / dmax |
| ActFD_WWTP | Actual filling degree of the last collector tank at the WWTP |
| AvgFD | Average filling degree = (ActFD + ActFD_WWTP) / 2 |
| **no control** | |
| u | = IF d<on1 THEN 0 ELSE IF d<on2 THEN q1 ELSE q1 + q2 |
| **Strategy "average filling"** | |
| u0 | Given parameter |
| u1 | Given parameter |
| e | = ActFD – AvgFD |
| y_Tr | = on1 / dmax |
| K_P | = 2*u2 |
| uhelp | = e * K_P |
| u2 | = (q1 + q2) |
| u | = IF ActFD>y_Tr THEN u2 ELSE IF (uhelp<u1 THEN u0 ELSE IF uhelp>u2 THEN u2 ELSE uhelp |
| **Strategy "WWTP load"** | |
| u0 | Given parameter |
| u1 | Given parameter |
| u2 | Given parameter |
| K_P | = u2 |
| uhelp | = IF ActFD_WWTP<= 0 THEN K_P * adjust ELSE IF ActFD_WWTP<1 THEN K_P * adjust * (1 - ActFD_WWTP) ELSE 0 |
| u | = IF uhelp<u1 THEN u0 ELSE IF uhelp>u2 THEN u2 ELSE uhelp |
| **For 2 branches** | |
| adjust | = 1 + ActFD3 - ActFD11 |
| **For 3 branches** | |
| adjust (Tank 3) | = 1 + ActFD3 - (ActFD11 + ActFD25) / 2 |
| adjust (Tank 11) | = 1 + ActFD11 - (ActFD3 + ActFD25) / 2 |
| adjust (Tank 25) | = 1 + ActFD25 - (ActFD3 + ActFD11) / 2 |

ties are equally filled, then the overall system capacity is utilized in the most optimal way.

The second strategy primarily considers the filling degree of the last storage structure upstream from the WWTP, and secondary of the other controlled structures as well. The manipulated variables of each structure are inversely related to the filling of this "last" tank, this way as filling degree increases there, the capacity of the upstream pumps are decreased, and the openings of the controlled sluice gates lowered. In addition, the magnitude of the manipulated variables is adjusted according to the ratio of the local and remote filling degrees (considering for this additional adjustment only filling of structures that are controlled, e.g., not the wet well at node 4). This means that if a tank has a higher filling degree than another, then release from there is increased, while release from the other is decreased. This strategy represents more of a physical design strategy than the previous one: the most downstream wet well has a design capacity related to the WWTP capacity (hence the abbreviated name: WWTP load), which should not be exceeded.

## Implementation of RTC

This work analyses advantages and disadvantages of RTC compared to non-controlled operation of sewer networks, especially under changing climate conditions. To provide a better picture of the system, a few aspects of the "no control" case are described here first.

At rising mains, where gravitational flow is not possible, pump stations transport the sewage from the storage tanks back to the sewer system. At these locations pumps operate depending on the water level in the storage facilities with given capacities and water levels turn the pumps only on and off. Sluice gates in the non-controlled case operate with fixed openings, which are left unaltered throughout the simulation period.

The difference with the RTC cases is the varying capacity of the pumps (i.e., variable speed pumps), the varying openings of sluice gates, and that these variables depend on global variables, such as the arithmetic mean of the filling degrees of several storage facilities. Consequently, at each time-step in the simulation period, these are recalculated and changed. Valid values of these manipulated variables feature upper, lower and turnoff limits, regulating the operation of the controlled structures between limits. The limits are set to match the "no control" case. This means that the pump capacities are maximized at the same level as the maximum pump capacity at "no control", and are minimized at zero, and turned off when below 5% of the maximum capacity. Gate openings are maximized at the diameter of the conduits they are attached to, and are minimized at zero, and turned off (closed) when below 0.05 m opening (BIOMATH 2006).

### Control mechanisms in catchment A

The upper scheme on Fig. 2 shows the schematic view of catchment A. The last conduit of the left branch is a rising main of a pump station, with no gravitational flow (from node 3 to 4). The capacity of the pump is the first possible variable that allows application of RTC here. The flow from the right branch (nodes 4–17) goes through a sluice gate at node 17. This is the second structure that allows RTC in the catchment. The two storage tanks are placed next to a pump station and a sluice gate; at node 3 / ST1 (pump station at the rising main, with installed capacity 1200 $m^3$) and at node 11 / ST2 (at sluice gate, with installed capacity 1600 $m^3$, see also Table 1).

The strategy "average filling" balances loads of the sewer network between the available storage tanks. For this reason the tanks need to be hydraulically connected to each other, in such a way that the flow from the upstream tank can be controlled and retained if needed before it flows to the downstream tank. The layout of the catchment postulates the separate management of the two branches for this control strategy, because there is no direct hydraulic connection between those storage branches or storage facilities, a typical layout for many sewer systems. Therefore, when applying this strategy, equal filling of storage tanks at node 4 and 3 (ST1) is one objective, and independently from this, equal filling of storage tanks at nodes 4 and 11 (ST2) is another one. Consequently, in this study, two separate arithmetic means of filling degrees are calculated for each branch. Figure 6 shows the schematic layout of the KOSIM-WEST implementation of this strategy.

The strategy "WWTP load" adjusts controlled structures based primarily on the filling of the wet well at node 4. Simply, the pump capacity (between nodes 4 and 3) and the opening of the sluice gate (node 17) are reduced as the storage tank at node 4 fills up. In the extreme situation of complete filling, both the pump capacity and the gate opening are zero. In a different situation, arbitrarily assuming a 50% filling degree at node 4, which allows some flow from both branches, the filling degrees of node 3 (ST1) and node 11 (ST2) are compared, and in case this value is higher at node 3, the pump capacity (between nodes 3 and 4) is slightly reduced, while the gate opening at node 11 is slightly increased. Figure 6 shows the implementation of this strategy in KOSIM-WEST (only the difference is shown compared to "average filling" on the upper right corner of the figure).

### Control mechanisms in catchment B

The lower scheme on Fig. 2 shows the schematic view of catchment B. For the same reasons as for catchment A, the strategy "average filling" considers the branches separately. Three different arithmetic means of filling degrees are calculated, one for each main branch (3–4, 25–4, 11–4), and another one for a side branch (27–11). Nodes 3 and 27 are pump stations, while nodes 25 and 11 are sluice gates.

In the strategy "WWTP load" the same structures are controlled. Similarly to the case in catchment A, these are operated in inverse relation to the filling degree of node 4 (node 11 in the case of the side branch (27–11)). The higher the filling degree at these becomes, the smaller the amount of water is released from the controlled structures upstream. The controllers on the main branches are also interrelated, as the ratio between the local filling degree and the arithmetic mean of the filling degrees at remote structures increase or reduce the controller output values (capacity of the pumps or opening of the sluice gates). This strategy is simply the expansion of the one applied in catchment A, applying the same principles to more than two controlled storage structures.

### Performance indicators

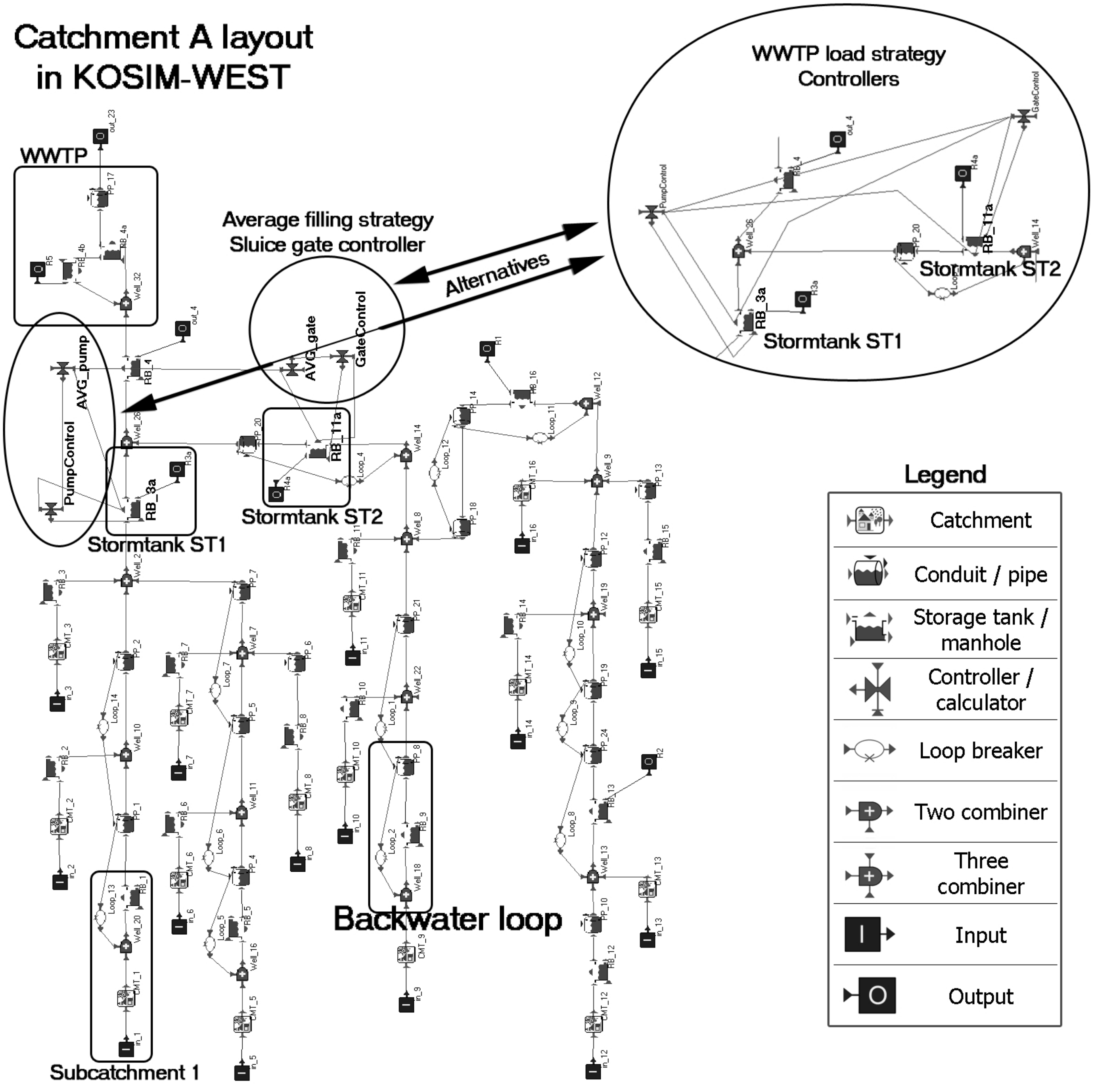
In this work, the CSO events serve as the basis for the performance analysis when evaluating and comparing the different scenarios. One CSO event in this study is defined as: "flow exceeding 10 L/s for at least 10 minutes at one CSO structure" (equivalent to 6 $m^3$ in 10 min). If the flow continuously remains above 10 L/s for a longer period, then it is still counted as one event. In the opposite case, as soon as the flow drops below 10 L/s, the event is finished, and in case of exceeding this value again, another event is started (assuming the minimum 10 min duration in both cases). No further analyses were carried out for evaluation (e.g., the frequency, distribution, magnitude, etc. of CSO events are neglected). It has to be noted that this definition of CSO events does not consider various features of the actual storm events or the precipitation data, contrary to some national and international legislations.

## Results

### General results

The simulation results are evaluated by number and volume of CSO events throughout the simulation period (365 days in all cases). Combined sewer overflows can only occur at CSO structures, which are at nodes 3, 11, 13, and 16 in catchment A (Fig. 2, upper scheme), and at nodes 2, 3, 8, 10, 11, 13, 16, 19, 25, 26, and 27 in catchment B (Fig. 2, lower scheme). The hydraulic structure of the catchments ensures that CSO events at certain structures are not influenced by the existence or lack of RTC. In catchment A, these structures are nodes 13 and 16, and in catchment B these are nodes 2, 8, 13, 19. This is because the structures are located far upstream of controlled structures, and thereby

**Fig. 6.** KOSIM-WEST scheme of catchment A with implmented control for “average filling” strategy (main picture) and “WWTP load” (altenative layout, top right). Major features are marked by frames.



controller operation only rarely causes spilling at these structures.

The results are summarized as tables of total and maximum spilled volumes and number of CSO events.

The discussion below provides a detailed analysis of the results. Here the most important aspects are highlighted. Compare and note the relation of the results obtained when applying different RTC strategies: “average filling” gives higher values than “no control”, while “WWTP load” leads to lower values than “no control”. Also note the relative differences in each result group when comparing the different climates. These relations do not reflect the ratio of the actual annual precipitations shown in Table 2. Also note that depending on the result variable (number of spills, maximum volume spilled or total volume spilled), these ratios might differ from each other.

## Specific results at catchment A

Table 4 summarizes the spilled volume and number of CSO events for each climate, storage tank, and CSO structure. It shows the number of CSO events on the left side and the maximum volumes spilled on the right side. The

**Table 4.** Catchment A, summary of number of CSO events (left) and maximum volumes spilled in a single CSO event (right, given in m$^3$).

| | Number of CSO events | | | | | Maximum volume spilled | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | Brussels | Dresden | Innsbruck | Palermo | Mean* | Brussels | Dresden | Innsbruck | Palermo | Mean* |
| **No control** | | | | | | | | | | |
| R3a | 19 | 25 | 32 | 30 | 27 | 2 869 | 10 363 | 5 240 | 10 047 | 7 130 |
| Node 4 | 6 | 17 | 16 | 18 | 14 | 2 671 | 2 725 | 1 872 | 5 117 | 3 096 |
| R4a | 0 | 2 | 3 | 6 | 3 | 0 | 1 672 | 594 | 1 077 | 836 |
| R2 | 17 | 24 | 28 | 34 | 26 | 1 031 | 4 472 | 2 316 | 4 249 | 3 017 |
| R1 | 29 | 42 | 37 | 45 | 38 | 1 103 | 4 243 | 2 231 | 4 123 | 2 925 |
| Sum | 71 | 110 | 116 | 133 | | 7 675 | 23 475 | 12 253 | 24 613 | |
| **Average filling** | | | | | | | | | | |
| R3a | 100 | 136 | 103 | 112 | 113 | 3 374 | 10 625 | 6 231 | 10 574 | 7 701 |
| Node 4 | 16 | 25 | 26 | 28 | 24 | 1 941 | 2 805 | 1 596 | 4 292 | 2 659 |
| R4a | 9 | 15 | 17 | 24 | 16 | 481 | 2 016 | 1 749 | 2 091 | 1 584 |
| R2 | 19 | 24 | 28 | 33 | 26 | 1 029 | 4 472 | 2 317 | 4 242 | 3 015 |
| R1 | 28 | 42 | 37 | 45 | 38 | 1 101 | 4 245 | 2 233 | 4 116 | 2 924 |
| Sum | 172 | 242 | 211 | 242 | | 7 925 | 24 163 | 14 126 | 25 315 | |
| **WWTP load** | | | | | | | | | | |
| R3a | 10 | 21 | 19 | 25 | 19 | 5 580 | 12 516 | 6 268 | 13 657 | 9 505 |
| Node 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| R4a | 0 | 2 | 1 | 5 | 2 | 0 | 1 403 | 338 | 778 | 630 |
| R2 | 19 | 24 | 28 | 34 | 26 | 1 022 | 4 472 | 2 314 | 4 253 | 3 015 |
| R1 | 29 | 42 | 37 | 45 | 38 | 1 096 | 4 245 | 2 230 | 4 126 | 2 924 |
| Sum | 58 | 89 | 85 | 109 | | 7 698 | 22 637 | 11 150 | 22 815 | |

*Arithmetic means are rounded to whole numbers.

four climatic archetypes are shown in separate columns, while the CSO locations are shown in rows. A sum value is included for each climate ("SUM" rows in the table), and a mean value is included for each control structure ("Mean" columns in the table). There are three blocks below each other on both sides, the first block showing results of "no control", the second block shows results of "average filling", and the last one shows the results of "WWTP load". Table 5 shows total volume spilled in the same structure.

The locations are indicated by their KOSIM-WEST references. R1 and R2 are CSO structures on the right branch at nodes 16 and 13 consequently (no storage at these locations), R4a and R3a are CSO structures of storage tanks at nodes 11 (ST2) and 3 (ST1) consequently, and node 4 is simply marked as "4" on Fig. 2.

For preliminary analysis, compare the "Sum" values of different blocks with each other. This way the performance of the RTC strategies are compared (for example the values shown at "average filling" are higher than at "no control", which shows that "average filling" performs worse than "no control"), etc. To compare the performance of the same setup (catchment and RTC), look at "Sum" values at different columns.

### Specific results at catchment B

Just like in the case of catchment A, three tables (the combination of two in Table 6 and a single one in Table 7) summarize the number of CSO events and the spilled total and maximum volumes for each climate and CSO structure.

The structure of the tables follows the same logics as in the previous results for catchment A, the only difference is the larger number of CSO structures, and therefore the larger number of rows in each table. Catchment B features 12 CSO structures, so the three control cases ("no control", "Average filling", and "WWTP load", form the three main blocks of the tables) contain 12+1 lines including the sum values as well. Again, the columns of tables show results of the four climatic archetypes.

Similarly to catchment A, compare the various blocks with each other first. Note that in this larger catchment, there are more CSO locations, and therefore more components to sum up than in catchment A.

## Discussion

### General conclusions deduced from the two virtual case studies

Both RTC strategies in this study were applied unaltered in all four climatic archetypes, but it must be recognized that fine-tuning of these strategies according to climatic differences might improve the results (reduce number of spills and spilled volumes). Since RTC strategy improvement is not part of this study, the strategies are left similar, which is a generally acceptable setup for the purpose of this experiment.

Another important general remark is the approximate similarity of the results at certain locations throughout all simulation cases (see greyed rows in Table 4, Table 5, Table 6 and Table 7). These locations are R1 and R2 in case of catchment A, and R2, R9, R10, R11, R12 in case of catchment B. Absence or existence of RTC practically does not affect the results here due to hydraulic reasons in the catch-

**Table 5.** Catchment A, summary of total spilled volumes ($m^3$).

| Location | Brussels | Dresden | Innsbruck | Palermo | Mean* |
|---|---|---|---|---|---|
| | **Total volume spilled** | | | | |
| **no control** | | | | | |
| R3a | 12 202 | 39 058 | 45 600 | 62 554 | 39 854 |
| Node 4 | 3 755 | 10 551 | 15 151 | 20 167 | 12 406 |
| R4a | 0 | 2 561 | 797 | 2 685 | 1 511 |
| R2 | 4 680 | 15 850 | 18 886 | 26 052 | 16 367 |
| R1 | 7 026 | 18 350 | 21 195 | 28 179 | 18 687 |
| Sum | 27 664 | 86 368 | 101 629 | 139 636 | |
| **Average filling** | | | | | |
| R3a | 44 484 | 77 703 | 84 230 | 99 443 | 76 465 |
| Node 4 | 5 126 | 12 854 | 14 417 | 18 470 | 12 717 |
| R4a | 1 578 | 7 001 | 8 887 | 11 087 | 7 138 |
| R2 | 4 667 | 15 846 | 18 886 | 25 997 | 16 349 |
| R1 | 7 023 | 18 346 | 21 186 | 28 112 | 18 667 |
| Sum | 62 878 | 131 750 | 147 604 | 183 108 | |
| **WWTP load** | | | | | |
| R3a | 12 191 | 40 239 | 51 119 | 71 177 | 43 682 |
| Node 4 | 0 | 0 | 0 | 0 | 0 |
| R4a | 0 | 1 935 | 338 | 2 132 | 1 101 |
| R2 | 4 715 | 15 856 | 18 915 | 26 036 | 16 381 |
| R1 | 7 097 | 18 351 | 21 225 | 28 182 | 18 714 |
| Sum | 24 003 | 76 381 | 91 599 | 127 527 | |

*Arithmetic means are rounded to whole numbers.

ment layout: only backwater could cause spilling there, but it is not possible because there are other CSOs located downstream from them, which spill before this could happen at these locations.

The actual design details of both catchments were determined according to Flemish (Belgium) design rules, which are developed to minimize CSOs with static operation of the system (no RTC). For this reason, it is not expected that RTC would largely improve the case of the Oceanic (Brussels) climatic archetype, since the rules followed in the catchment design were developed for the same particular purpose as the RTC was implemented for. More interesting is how the same design criteria are performing under different climatic conditions, and how much RTC can limit the reduction in performance due to “poor” (meaning climatically non-consistent) design. Please note, that if the load (here rainfall) is homogenous (similar time series are used for all subcatchments, as here), then a single optimum system design (specifying conduit and throttle discharges) exists for a static case. The applied design criteria followed these rules. In the present experiment, RTC adjusts the throttle discharges. But since the system is optimized for average filling for a static case anyway, there is little chance to improve it by RTC, especially by a strategy aiming at average filling of storage volumes.

In general the strategy “average filling” worsens the situation both regarding spilled volume and CSO events compared to the “no control” case, as results are, in general, higher with this RTC strategy. On the other hand, “WWTP load” shows improvements both in spilled volume and in number of CSO events. This finding is valid for both catchments.

It is assumed that the strategy “average filling” would give better results, if a direct, two-way hydraulic connection between the storage tanks existed. If the control system is not able to redistribute sewage from one tank to the other, then the strategy will not operate as expected. As is visible from the schemes of the catchments (Fig. 2), only catchment B features such a connection to some extent. Therefore the strategy “average filling” cannot perform well in the tested catchments.

Obvious differences between the results of the climatic scenarios show that the general rules followed when applying the PASST methodology do not function as expected. Please note that the PASST guidelines (see Table 1) are meant to be used for tests regarding existing catchments, where climate is already reflected in the design. Therefore the guidelines themselves do not need to include climate-related features. In the present case the guidelines were applied for designing the catchments, which is an uncommon application of PASST. This indicates that other features besides the ones listed in Table 1 (e.g., climate or load) might also be important to consider when designing virtual catchments for similar purposes as here. Alternatively, real catchments could also be used for the tests, and thus avoiding the problems related to design.

## Catchment A

Relative improvements are observed in the case of Oceanic climate (Brussels, 13%), but largest improvements in absolute terms are obtained for the Mediterranean climate (Palermo, 12 109 $m^3$). The absolute values of volumes are calculated by subtracting the RTC results from the “no control” results, and the percent values by dividing these with

**Table 6.** Catchment B, summary of number of CSO events (left) and maximum volumes spilled in a single CSO event.

| | Number of CSO events | | | | Maximum volume spilled | | | |
|---|---|---|---|---|---|---|---|---|
| Location | Brusels | Dresden | Innsbruck | Palermo | Brussels | Dresden | Innsbruck | Palermo |
| **no control** | | | | | | | | |
| R6a | 1 | 2 | 2 | 3 | 265 | 10 854 | 5 496 | 16 463 |
| R3a | 2 | 10 | 16 | 16 | 7 657 | 19 539 | 8 139 | 21 622 |
| R4a | 0 | 2 | 3 | 4 | 0 | 40 653 | 13 830 | 50 206 |
| R7a | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| R8a | 2 | 8 | 10 | 10 | 5 510 | 18 399 | 6 852 | 19 836 |
| Node 4 | 4 | 13 | 16 | 14 | 17 838 | 12 104 | 8 478 | 7 722 |
| R12 | 4 | 14 | 17 | 20 | 6 028 | 15 176 | 6 510 | 15 615 |
| R11 | 0 | 1 | 0 | 3 | 0 | 3 378 | 0 | 3 972 |
| R2 | 0 | 2 | 3 | 5 | 0 | 15 682 | 5 210 | 16 122 |
| R1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| R10 | 1 | 6 | 11 | 14 | 15 640 | 29 578 | 16 887 | 37 677 |
| R9 | 2 | 8 | 12 | 15 | 5 161 | 16 788 | 6 712 | 18 175 |
| SUM | 16 | 66 | 90 | 104 | 58 099 | 182 150 | 78 114 | 207 411 |
| **Average filling** | | | | | | | | |
| R6a | 1 | 2 | 2 | 3 | 253 | 10 824 | 5 466 | 16 467 |
| R3a | 33 | 44 | 45 | 39 | 11 889 | 23 779 | 12 853 | 26 465 |
| R4a | 4 | 7 | 14 | 17 | 543 | 7 314 | 2 933 | 7 200 |
| R7a | 8 | 14 | 17 | 25 | 1 335 | 7 739 | 4 313 | 8 324 |
| R8a | 48 | 41 | 57 | 54 | 11 968 | 24 864 | 13 304 | 26 326 |
| Node 4 | 5 | 19 | 16 | 19 | 18 033 | 11 828 | 10 731 | 29 204 |
| R12 | 4 | 14 | 17 | 20 | 6 023 | 15 169 | 6 504 | 15 653 |
| R11 | 0 | 1 | 0 | 3 | 0 | 3 355 | 0 | 3 973 |
| R2 | 0 | 2 | 3 | 5 | 0 | 15 667 | 5 173 | 16 164 |
| R1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| R10 | 1 | 6 | 11 | 14 | 15 627 | 29 573 | 16 858 | 37 717 |
| R9 | 2 | 8 | 12 | 15 | 5 155 | 16 788 | 6 707 | 18 199 |
| SUM | 106 | 158 | 194 | 214 | 70 826 | 166 902 | 84 844 | 205 693 |
| **WWTP load** | | | | | | | | |
| R6a | 1 | 2 | 2 | 3 | 262 | 10 856 | 5 484 | 16 518 |
| R3a | 4 | 14 | 16 | 18 | 17 455 | 32 435 | 19 296 | 42 934 |
| R4a | 0 | 1 | 0 | 3 | 0 | 5 234 | 0 | 4 370 |
| R7a | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| R8a | 3 | 9 | 13 | 15 | 15 307 | 27 115 | 17 014 | 35 729 |
| Node 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| R12 | 4 | 14 | 17 | 20 | 6 026 | 15 182 | 6 508 | 15 670 |
| R11 | 0 | 1 | 0 | 3 | 0 | 3 367 | 0 | 3 975 |
| R2 | 0 | 2 | 3 | 5 | 0 | 15 675 | 5 191 | 16 168 |
| R1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| R10 | 1 | 6 | 11 | 14 | 15 637 | 29 564 | 16 879 | 37 710 |
| R9 | 2 | 8 | 12 | 15 | 5 161 | 16 777 | 6 712 | 18 195 |
| SUM | 15 | 57 | 74 | 96 | 59 849 | 156 206 | 77 083 | 191 267 |

the “no control” results. The majority of the CSO reduction is observed in both cases at node 4 (the example figures relate to total volume).

Looking at the result summaries at each location, spills at almost all important locations (R3a, R4a, node 4) are increased for “average filling” and partly reduced or kept similar for “WWTP load”.

Comparing climate-related issues, the Oceanic (Brussels) climate causes the least volume of CSOs, while the Mediterranean (Palermo) causes the most. Continental (Dresden) and Alpine (Innsbruck) climates are placed in between these extremes. The number of spills shows somewhat different features, because with both RTC strategies this number is lower in Alpine climate conditions (Innsbruck) than in Continental conditions (Dresden). The performance indicator “maximum volumes spilled” shows less variation than the two other indicators. But figuratively speaking, the “redistribution” of spills (i.e., the same total volume, but at different locations) is observed when comparing “no control” and “WWTP load” cases, as the volume spilled at R3a and node 4 at “no control” is equivalent to the volume spilled at R3a at “WWTP load”. There are no similar phenomena at “average filling”. Clearly, the “average filling” strategy does not operate in the expected way, which indicates a lim-

**Table 7.** Catchment B, summary of total spilled volumes (m$^3$).

| Location | Brussels | Dresden | Innsbruck | Palermo |
|---|---|---|---|---|
| **no control** | | | | |
| R6a | 265 | 13 325 | 7 079 | 37 532 |
| R3a | 8 694 | 39 326 | 47 301 | 87 214 |
| R4a | 0 | 50 373 | 36 521 | 134 993 |
| R7a | 0 | 0 | 0 | 0 |
| R8a | 5 567 | 34 908 | 32 447 | 69 647 |
| Node 4 | 21 872 | 40 910 | 65 597 | 56 547 |
| R12 | 9 341 | 42 635 | 50 200 | 75 227 |
| R11 | 0 | 3 378 | 0 | 5 940 |
| R2 | 0 | 20 449 | 7 610 | 43 401 |
| R1 | 0 | 0 | 0 | 0 |
| R10 | 15 640 | 56 819 | 63 603 | 126 756 |
| R9 | 5 434 | 34 041 | 33 550 | 66 696 |
| SUM | 66 813 | 336 164 | 343 907 | 703 954 |
| **Average filling** | | | | |
| R6a | 253 | 13 248 | 7 025 | 37 556 |
| R3a | 41 909 | 112 147 | 130 609 | 168 519 |
| R4a | 1 095 | 15 184 | 16 480 | 31 402 |
| R7a | 2 838 | 22 201 | 23 270 | 32 848 |
| R8a | 54 392 | 115 446 | 139 842 | 176 676 |
| Node 4 | 23 914 | 55 298 | 75 716 | 109 474 |
| R12 | 9 318 | 42 478 | 50 131 | 75 292 |
| R11 | 0 | 3 355 | 0 | 5 930 |
| R2 | 0 | 20 382 | 7 502 | 43 523 |
| R1 | 0 | 0 | 0 | 0 |
| R10 | 15 627 | 56 744 | 63 539 | 126 884 |
| R9 | 5 425 | 33 841 | 33 503 | 66 796 |
| SUM | 154 771 | 490 327 | 547 616 | 874 901 |
| **WWTP load** | | | | |
| R6a | 262 | 13 323 | 7 061 | 37 642 |
| R3a | 21 288 | 79 575 | 95 369 | 169 338 |
| R4a | 0 | 5 234 | 0 | 10 536 |
| R7a | 0 | 0 | 0 | 0 |
| R8a | 16 867 | 63 203 | 76 637 | 135 713 |
| Node 4 | 0 | 0 | 0 | 0 |
| R12 | 9 311 | 42 648 | 50 128 | 75 251 |
| R11 | 0 | 3 367 | 0 | 5 955 |
| R2 | 0 | 20 456 | 7 567 | 43 506 |
| R1 | 0 | 0 | 0 | 0 |
| R10 | 15 637 | 56 810 | 63 464 | 126 867 |
| R9 | 5 434 | 34 043 | 33 472 | 66 781 |
| SUM | 68 800 | 318 658 | 333 698 | 671 589 |

**Note:** Arithmetic means are rounded to whole numbers.

itation of applying this type of RTC to catchment A. The results show that there is a large increase in spilling at R3a and at node 4 as well. The only slight improvement is observed at node 4 when subjecting the sewer system to Innsbruck and Palermo climates, but these cannot compensate for the overall bad performance of the strategy at other locations and climates.

Please note that by means of the applied RTC, it is possible to operate the system in such a way, that CSOs are relocated. This feature has major implications on sewer system operation considering stress-zones in the catchment. Stress-zones are locations that are more sensitive to CSOs than others, for example the ecosystems. Combined sewer overflows in the neighbourhood of ecologically sensitive areas can be reduced or avoided by selecting the proper RTC strategy.

The "WWTP load" strategy in general improves the situation for most climates by slightly increasing CSOs at R3a, but reducing or completely eliminating them at node 4 and R4a. The slight increase at R3a is still less than the reduction at other locations. The strategy slightly worsens the case for the Oceanic climate (Brussels, in case of maximum volume spilled), but improves the cases at other climates.

## Catchment B

Results from the "average filling" strategy show that both the total volume spilled and the number of spills increase compared to the "no control" case. Surprisingly, the maximum volume spilled is reduced in Dresden and Palermo, but increased in Brussels and Innsbruck. This again could indicate a limitation of applying this type of RTC to catchment B.

The "WWTP load" strategy on the other hand shows mostly improvements compared to the "no control" case, as there are reduced total spills, number of spills and reduced or similar magnitudes of maximum volume spilled. The case of Oceanic climate (Brussels) is an exception, because in this case the indicators do not show improvement with RTC. We also see that spills at node 4 are eliminated completely in all climates and are largely reduced at R4a. There are increases in general (considering means of different climates) at R3a and R8a, and no changes at R11, R10 and R9. This trend is repeated in cases of all other indicators, most clearly in total and maximum spills, and less obviously, but still clearly in number of spills as well.

## Conclusions

The presented work successfully demonstrated the application of the developed benchmarking methodology, as a general stepwise approach to analyse the effects of atypical climate and to evaluate RTC potential on sewer system performance. The steps followed were designing the virtual catchments, dual platform modelling and validation, selecting data, selecting RTC strategies, selecting performance indicators, and presenting and integrating results.

The RTC strategies were not adjusted to match the climatic differences of the tests. The strategies were evaluated by comparing CSO indicator values resulting from the "no control" case with those from RTC cases "average filling" and "WWTP load". This procedure was repeated for four climatic conditions.

Due to the guidelines that were followed when designing both virtual catchments, it seems reasonable that the Oceanic climate (Brussels) scenarios could not, or only little, be improved. This is because these design rules were originally optimized for this particular climate, and therefore the tests performed in other conditions (Continental, etc) show the potential of RTC in a non climate-optimized sewer system. This is practically a system with a sub-optimal design, which is a typical example for situations expected in the future's shifted climate.

The strategy "average filling" performed poorly in both catchments and all climates. Two of the indicators (total volume of CSOs and number of CSOs) showed worse results compared to the "no control" case, while the maximum spilled volume was somewhat similar. As the bad performance was not related to catchment size and structure, it seems that the controller strategy needs further investigations and improvements for better results. Obviously, the catchments are mostly incapable of utilizing this RTC strategy due to their layout. The results were worst in the Oceanic climate (Brussels), as expected, while the Mediterranean climate (Palermo) performed better.

The second tested strategy "WWTP load" improved the situation in both catchments. Although in case of the Oceanic climate (Brussels) the improvements are minor, not unexpected given its design, in the three other climates applying RTC caused reduction of total and maximum volume and number of CSOs.

The findings support the usefulness of a RTC development approach that considers both climate and catchment characteristics in the design phase of RTC implementation projects. The work presented a range of methods and measures that support studying the feasibility and setup of RTC systems through modelling and simulation.

## Recommendations and outlook

The approach described above explains a possible procedure of RTC simulations and design. Therefore the procedure may be followed without major alterations in other cases as well. Similar approaches in future works however, should consider a more detailed adjustment of each general RTC strategy to the actual control locations, catchments or to the various climates, and thus compare more refined alternatives. Indeed, in this study it could not be shown how much the schematic structure of the test catchments influenced the success or the failure of the RTC strategies. Alternative RTC strategies and affordable modifications to catchment layout are also of obvious interest for the future.

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