# Coupling real-time urban flood forecasting with pollution assessment

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## ABSTRACT

Urban floods represent an important risk for the population of cities. Indeed, due to the increasing concentration of people, the low infiltration capacity of the urban river basin and the limited space reserved for the river courses, severe damages during thunderstorms are expected. This trend can be tackled by appropriate planning measures, but the growth of cities is often faster than the risk mitigation plans.

For this reason, water resources and flood risk management can rely on information systems using coupled hydro-meteorological forecasting. Indeed, these tools create relevant information for flood control by reservoir and treatment plant optimization, for limitation of pollution inlets during flood events and for alerting the population to protect human lives.

The city of Morges in Switzerland developed an online riverflow and wastewater forecast system based on the RS2012-City rainfall-runoff model [1]. This model was firstly used to define the future investments needed to adapt to the growing population of the city. This task was achieved with the 1 year continuous simulation of future development scenarios (2040), after the model calibration and validation based on a 4 years period at hourly time steps. The results showed a need for increased hydraulic capacities of the wastewater network in order to mitigate the pollution increase as well as the increasing flooding risk. The model was then adapted for online forecasting.

The RS2012-City rainfall-runoff model is based on a high resolution semi-distributed concept [2]. The hydrological model is developed with the combination of multiple modified GR and SWMM models for each sub-basin. It uses rainfall and temperature gauging stations as input, as well as typical water consumption profiles for every sub-basin. It computes the different hydrologic functions such as stormwater and wastewater production, runoff, free surface and pressure flow, reservoir routing and flow diversion. Not only water discharge is computed, but also water quality is considered by the diffusion-advection model, including the erosion-deposition of solid particles. As a result, urban flood events can be predicted, as well as their consequences in terms of inflow into the treatment plants, location of pollution due to wastewater releases and anticipated inundated zones. All this information is communicated on a web platform.

## 1. INTRODUCTION

Water resources management in cities may be confronted with severe difficulties due to rapid population growth. On the one hand, there are two fundamental services in operation to guarantee a minimal safety level: providing high quality drinking water and collecting and treating of wastewater with a minimal impact on the environment. On the other hand, there is flood control, which can be of highest importance for people safety. Due to the increased impermeable portion of ground surface, the transfer of rainfall water from the city to the river or to the sea has to take higher hydraulic capacities into account. However, as it is not always possible to reduce the risk of damages completely, other mitigation measures have to be considered.

The Morges region is located in Switzerland, next to the city of Lausanne, lying at Lake Geneva. This region is facing very rapid population growth due to the economic development. Nevertheless, the spatial extension of the city is limited by the lake and the mountains, but the density of population is expected to increase in order to adapt to this socio-economic developments. It is predicted that the population will increase from 34’000 to 55’000 inhabitants within the next 25 years. In this context, the concentration of assets will strongly increase and the risk due to a flood situation will thus keep growing as well. The objectives of the authorities are to cope with this demographic development, but at the same time, to keep the negative impacts on the environment under control. This means that the sewer system must not produce higher direct overflow into the rivers and the lake, and the treatment capacity must be increased.

The modelling of flows in rivers and wastewater, stormwater or natural drainage networks is a helpful tool to gain a better knowledge on the river basin and of its flow conditions. Commonly, rainfall-runoff modelling approaches are applied. In this context, an innovative approach is developed in order to answer long-term planning questions, as well as to deal with operational challenges. This approach is developed based on the coupling of the RS2012-City semi-distributed rainfall-runoff model, supporting a decision-making process for long term planning strategies, with an operational forecasting system controlled by a web interface. The methodology applied in this project is based on the following stages:

1. Modelling of the basin, including wastewater and natural river network. In this model, the sub-basins can be urban basins (including impervious areas with wastewater inputs) as well as natural basins (where only natural hydrological processes are considered). Only the urban basins can feed the wastewater network. The natural river network can be fed by natural basins as well as spillovers issued from the urban drainage networks. The model is able to separate the different main contributions of water in the networks: wastewater, stormwater in the urban basin equipped with partially combined sewer system, and groundwater infiltration.
2. Calibration of the model based on observed meteorological data (precipitation and temperature, and generation of wastewater). The control values are discharge measurements in the sewerage network and at the entry of the wastewater treatment plant, as well as qualitative information related to the frequency of spillover of stormwater. The typical period for calibrating the model is one year at hourly time step.
3. Assessment of the drainage networks based on model results (reference state): portion of each water contribution (wastewater, stormwater, groundwater infiltration), portion of spilled wastewater at the stormwater overflows, hydraulic capacity limitations, hydraulic capacity reserve in wastewater network. This stage allows highlighting the major problems and limitations of the drainage networks.
4. Analysis of scenarios by comparing the results of the reference state (current situation) and the modified state (scenario). The different scenarios consider population growth and development of the urban basins, modifications of the wastewater networks due to new extensions, or adaptation of limiting sections.
5. Transformation of the system into a real-time monitoring system, including forecasting, in order to optimize the performance (or operation) of the treatment plant, to anticipate maintenance activities and to validate the assumptions of the model.

The following chapter will focus on the model description, the presentation of main outcomes of the system and scenario analysis, and the operational forecasting system.

## 2. MODEL DESCRIPTION

### 2.1. Model Concept

The RS2012-City model used in this study is a semi-distributed conceptual model. This means that the area to be modelled can be discretized into irregular sub-basins of typical areas ranging from 10 ha (urban basins) to 2000 ha (natural basins), according to the morphology of the river basin and the topology of the drainage networks. Figure 1 presents the project area in the Morges region in Switzerland illustrating the position of drainage networks. The irregular discretization in urban basins is clearly visible (gray polygons), as well as the combined wastewater network (red lines), the natural river network (blue lines) and the main storm spillways (orange point) and pumping stations (yellow points).

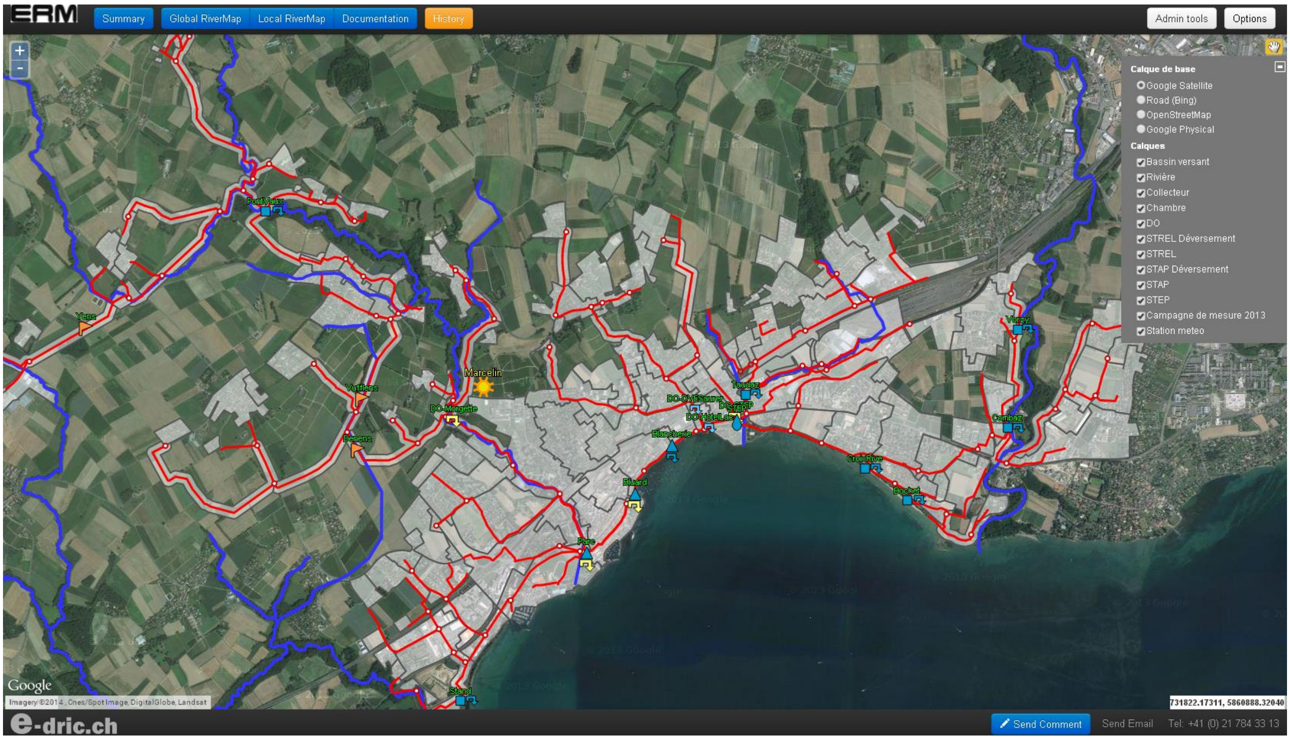


Figure 1: Overview of the project area in Morges, Switzerland. Blue : stormwater network and river courses ; Red : wastewater network ; Gray : urban sub-basins ; Points : meteo gauging station (orange), discharge gauging station (blue), stormwater overflow (yellow), pumping station (blue triangles).

The main components of the urban basin model are described in Figure 2. The processes are occurring from top to bottom, according to the sketch.

The input data of the system is the weather data, based on measurements at gauging stations, mainly precipitation and temperature. Additionally, hourly data of wastewater generation was defined by transforming, for every urban basin, a unit average wastewater discharge, which is multiplied by the number of equivalent-inhabitants (EH) in the basin. This average value is then transformed into hourly time series according to multiplication coefficients related to monthly, daily and hourly hydrographs.

The rainfall-runoff transformation for each urban basin is realized by a modified GSM-SOCONT model [2], which is a combination of GR3+ (enhanced GR3 model) and SWMM models. In addition to the GSM-SOCONT model parameters, more sensitive parameters have to be determined, based on a geographical and topological analysis. The permeability coefficient allows separating the permeable areas, where infiltration is possible, from the impervious areas, where all rainfall water is routed into the wastewater network without infiltration. In the permeable areas, the rainfall water is structured into infiltration, evaporation and runoff. The infiltrated water can flow back to the wastewater network according to the rate of groundwater infiltration. The latter links the soil saturation of permeable areas with the groundwater infiltration. In the impervious areas, the rainfall water flows to the natural drainage system, except the part related to the rate of combined system.

Summarized, there are two kinds of outlets for an urban basin. The first outlet is the wastewater network, where water issued from wastewater production (EU), stormwater issued from the combined sewer system (EP) and groundwater issued from infiltration (ECP) compose the total flow. The second outlet is the stormwater network or the natural drainage system where water issued from rainfall over permeable and impervious areas as well as infiltrated groundwater compose the total flow. Wastewater can also flow into the stormwater drainage system when storm spillovers are activated or when the capacity of the wastewater network is exceeded.

The purpose of this modelling concept is to represent the entire river basin, with all wastewater, stormwater and river flows, into a single model. It allows the analysis of the interactions between the different components of the drainage system, which often are the source of pollution problems.

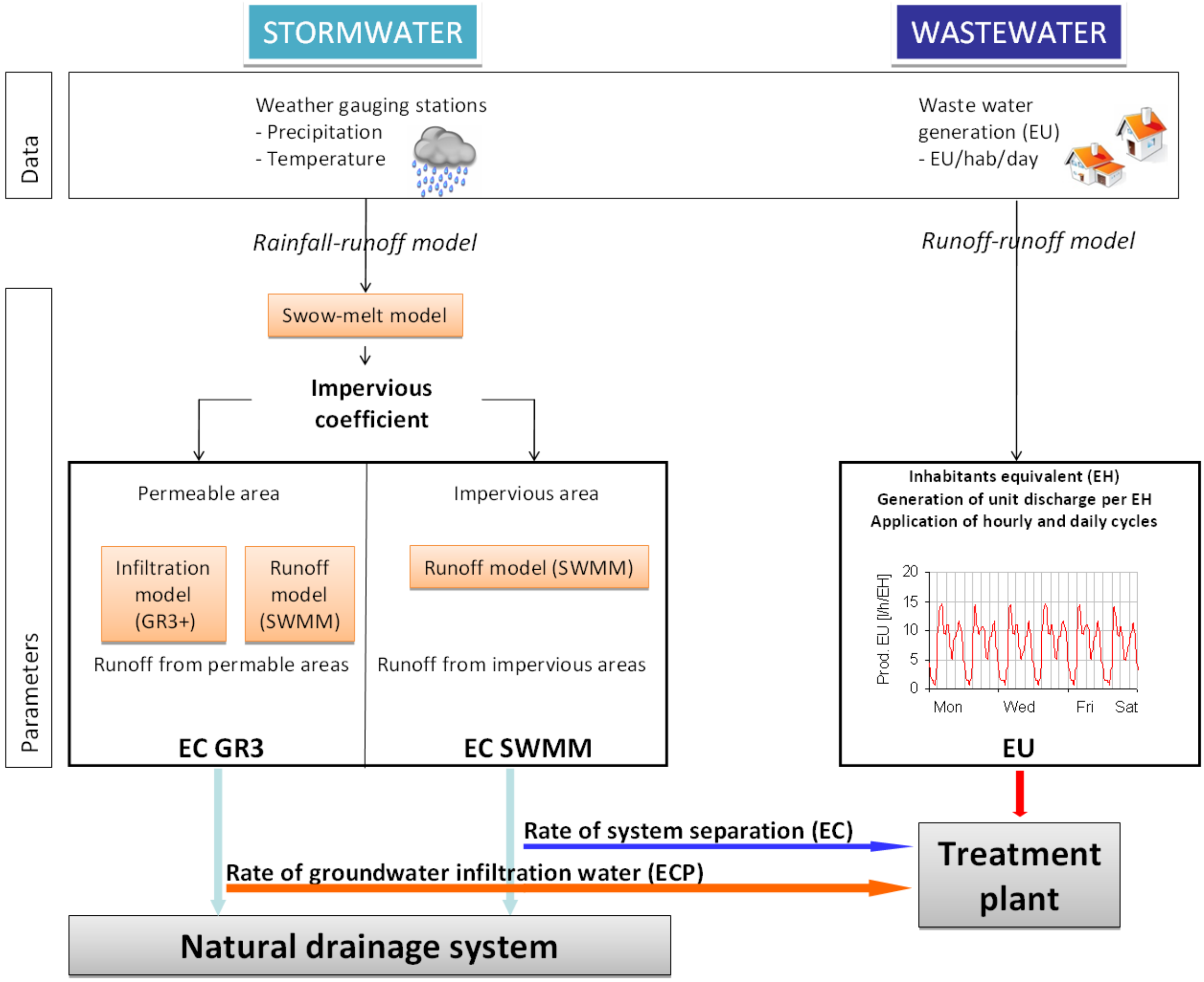


Figure 2: Description of the urban basin components, including input data (weather and wastewater data), main parameters (impervious coefficient, system separation rate and groundwater infiltration rate) and outputs of the drainage networks (treatment plant and natural river network).

Figure 3 shows an example of model established in RS2012-City. The combination of the different components of a complex urban river basin is visible. The link between the different basins is modelled by an arrow. In this example, it is shown how the model is able to combine natural basins and river reaches (left side) with urban basins and wastewater network facilities such as pipes, storm spillways, chambers and treatment plants (right side). The water can flow from any object to the other according to the topology of the river basin and the drainage networks.

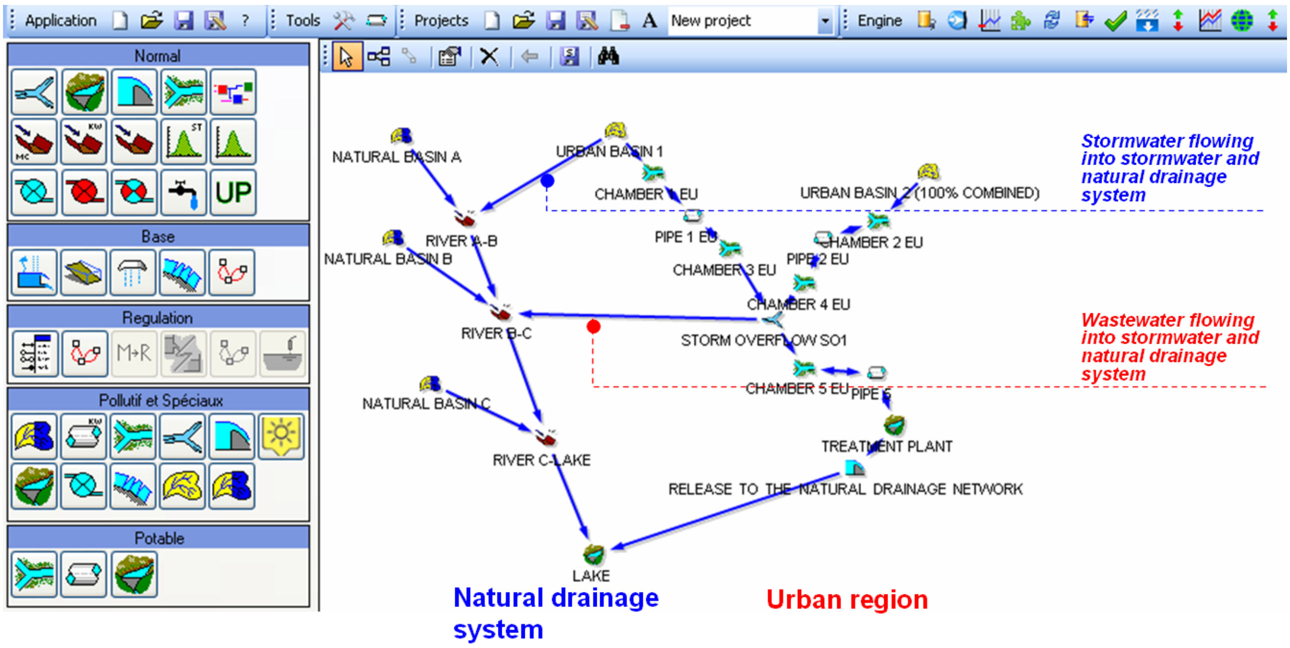


Figure 3: Modelling a complex river basin in the RS2012-City interface. Left side of the model: natural drainage system or stormwater network; right side of the model: wastewater system. The arrows indicate the principal flow direction, from top to bottom.

### 2.2. RS2012-City model

The RS2012-City model used in this study combines hydrological as well as hydraulic features. The main hydrological processes considered are the following, parameterized for every basin:

- Weather data interpolation: Shepard's method with external variables
- Snow-melt: GSM degree-day model (2 reservoirs, 3 parameters)
- Glacier-melt: GSM degree-day model (3 reservoirs, 3 parameters)
- Soil infiltration and evaporation: GR3+ model (2 reservoirs, 7 parameters)
- Surface runoff model: SWMM model (1 parameter)

The main hydraulic processes considered are the following, parameterized for every object:

- River flow: kinematic wave (1 parameter)
- Reservoir routing: combined regulation rules and water level-outflow relationships
- Pipe flow: hydrodynamic model combining free surface flow and pressure flow (1 parameter)
- Storm overflow: inflow/spill relationship
- Pressure flow in junctions: no consideration of volume storage in chambers (1 parameter)

For the pollution assessement, two additional components are implemented:

- Advection-diffusion model for the dissolved pollutants: this model allows to track the different water components (0 parameter)
- Erosion-deposition model for solid particles: model not used in this contribution (5 parameters for catchment solid particle production and 4 parameters for pipe erosion-deposition)

All objects (hydrological and hydraulic) are combined in the model. For this reason, very complex situations can be represented by the model. More details about the equations can be obtained from e-dric.ch, 2012 [3].

### 2.3. Model calibration

The model calibration was conducted using mainly inflow measurements at the Morges treatment plant located next to Lake Geneva. 4 years of hourly inflow were used ranging from 2008 to 2012.

Moreover, 12 additional local measurements located at different points of the wastewater network were for the model validation. These measurements were obtained during a 3 weeks period during spring 2006. Finally, a qualitative comparison between the simulated and observed spillovers was performed in order to check the correct hydraulic behaviour of the model.
Figure 4 presents the comparison between observed and simulated discharge at the inlet of the Morges treatment plant. The mean annual volume balance absolute error remains under 1%. The visual analysis shows that the model is able to represent the typical wastewater daily cycles, as well as the seasonal variability of the inflow with rapid increases of discharges during rainfalls and a slow decrease during recession periods. The model has a tendency to overestimate the highest discharges entering the treatment plant, due to uncertainties related to the estimation of real capacity of the treatment plant.

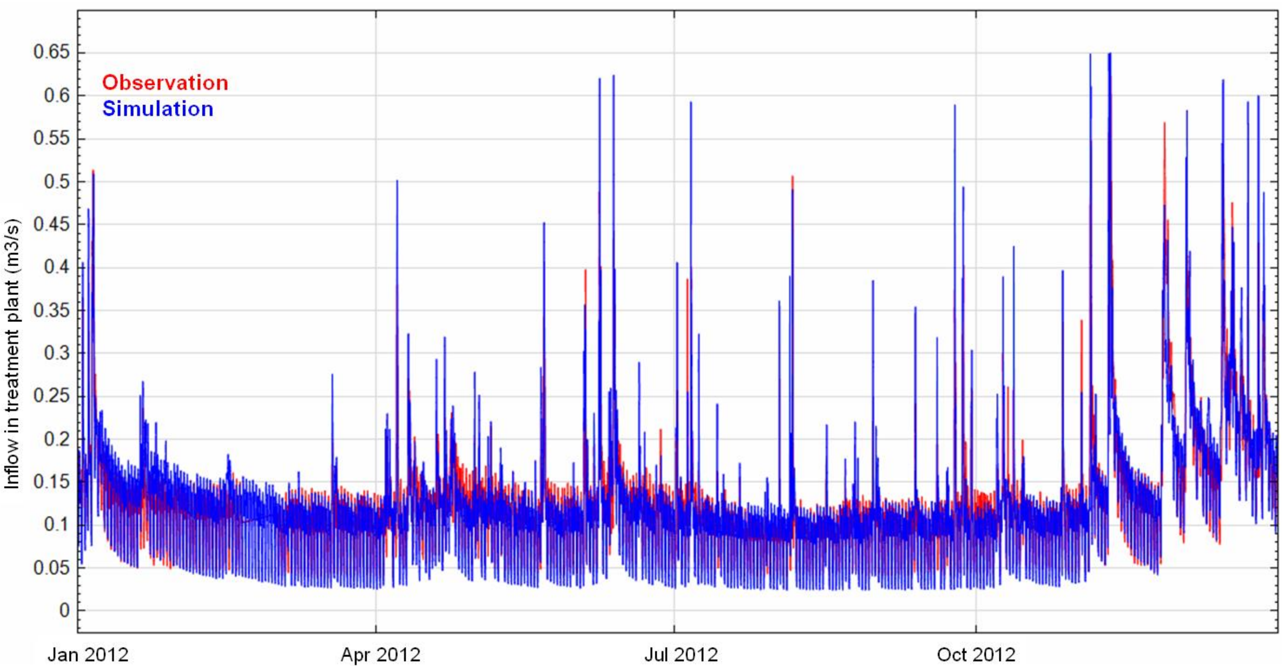


Figure 4: Comparison between observed and simulated inflow in the Morges treatment plant, year 2012, hourly time steps.

## 3. ANALYSIS OF THE WASTEWATER NETWORK IN MORGES

The main challenges for the city authorities of Morges are the reduction of the environmental impacts and risks during floods under a rapid growing population. In order to cope with these challenges, optimization and extension of the wastewater as well as stormwater networks are planned. Typically, the extension of the wastewater network including villages located in the outer areas of the city is planned, as well as the possibility to treat additional pollutants. The main objectives of the city authorities can be summarized as follows:

- Adaptation of the drainage capacity of the wastewater network to the growing population located inside the current basin
- Adaptation of the drainage capacity of the wastewater network to the new contributors located outside the current basin
- Maintaining of the environmental quality of the basin by avoiding any increase of the wastewater spillovers

In order to achieve these objectives, considering limited investments in new infrastructure, a detailed analysis has been performed with the RS2012-City model. The functioning of pumping stations or small storm overflows has been analyzed. Moreover, the verification of wastewater and groundwater inflow at a very local scale has been achieved. Indeed, the analysis of such local installations, when correctly handled, can lead to local pragmatic solutions with high efficiency. Moreover, the combination of multiple local solutions can prove as efficient as a new expensive infrastructure, such as the increase of the wastewater network capacity. The objective of this analysis is then to identify these local solutions to be combined, which will provide a suitable strategy to handle the economic regional development.

### 3.1. Analysis of the current drainage system

One of the major processes influencing the drainage capacity is the filling of the wastewater network by groundwater infiltration. In order to focus on the critical zones, the average annual rate of groundwater infiltration is presented in Figure 5. The red coloured areas and pipes are critical. However, the overall rate of groundwater infiltration at the treatment plant could be estimated at 31%, which is within the acceptance range.

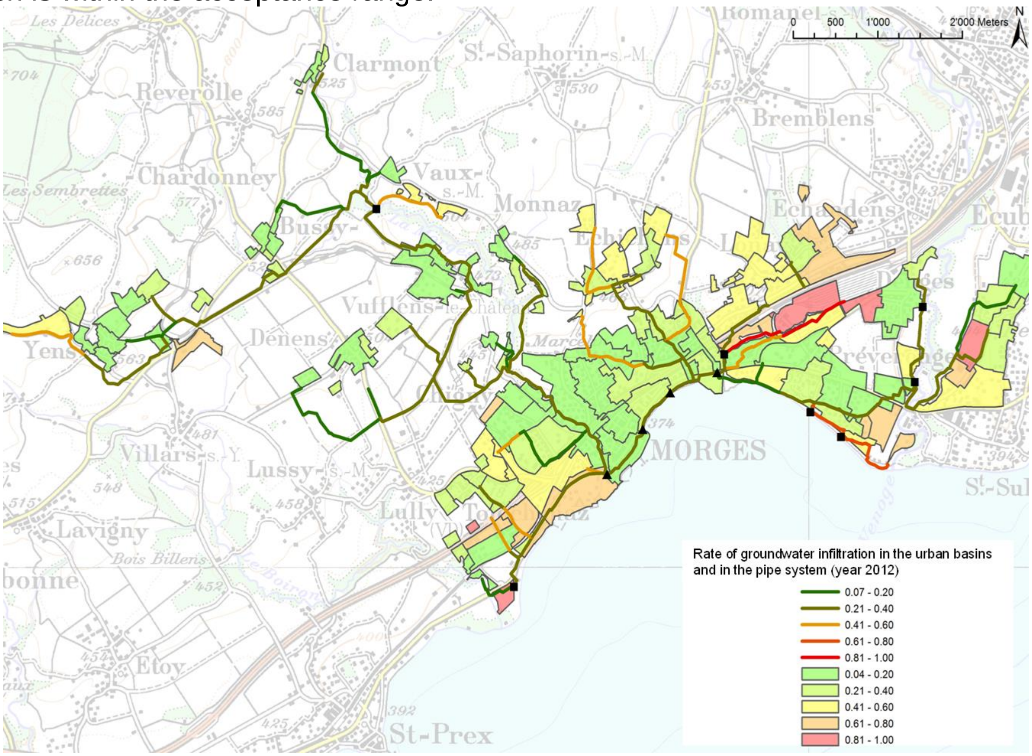


Figure 5: Average annual rate of groundwater infiltration in the urban wastewater network. Green: low rates; Red: critical rates.

Figure 6 shows the annual spilled volume of wastewater at the storm spillovers, pumping stations and network chambers, in relation with the average rate of separate system. The four spilling hot spots are located in the western part of the wastewater network. One pumping station located in the northwestern part of the basin causes the highest volumes of spilled wastewater into the natural river system. Other spots are located next to the lake, except one storm spillover located downstream of the critical pumping station. These elements contribute strongly to the limited drainage capacity of the wastewater network. In order to mitigate these problems, two types of measures are proposed:

- Increase the hydraulic capacity of the western part of the network, including a higher pumping capacity
- Reduction of the groundwater infiltration flowing from the northwestern part of the basin in order to offer more capacity to inflows from other basins

In fact, a detailed analysis of the inflows from the northwestern part of the basin revealed a seasonal groundwater infiltration during wet periods, explaining the high annual spilled volume of the pumping station. The source of the inflow is the infiltration into the 2 kilometres long pipe coming from the western part, and the infiltration in the village called Yens, at the upstream of this pipe. Currently, a field campaign is conducted in order to assess the source of these undesirable inflows.

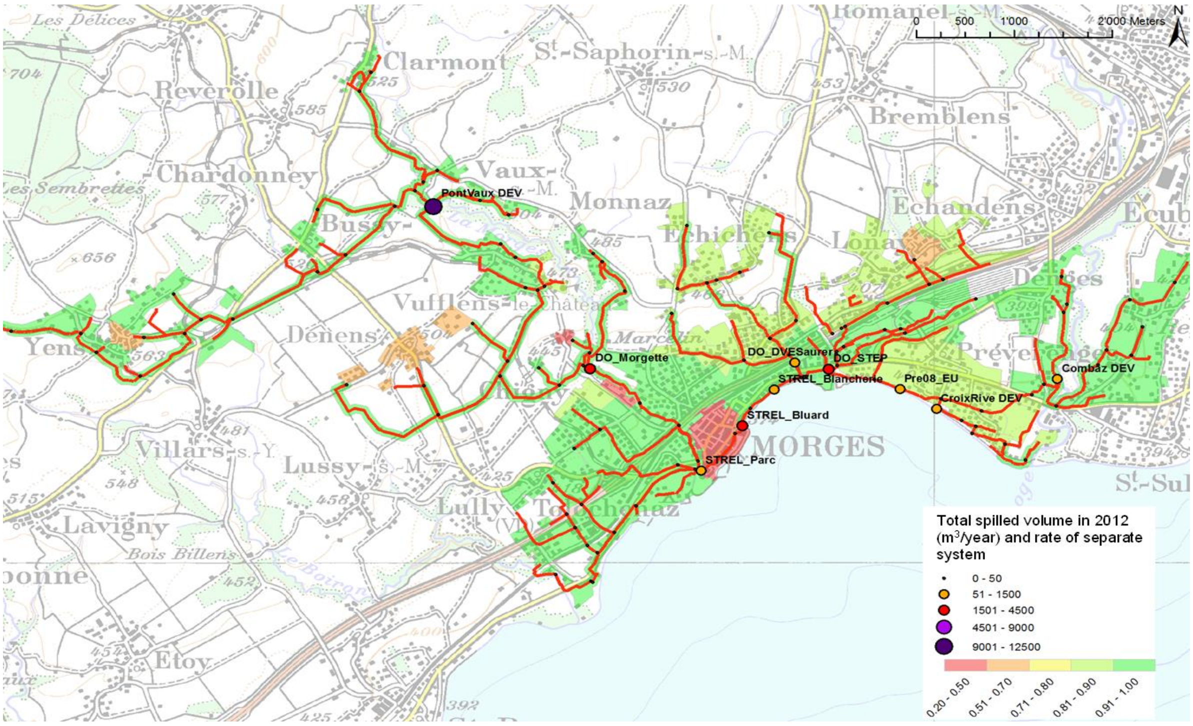


Figure 6: Annual spilling volume at the storm spillovers, pumping stations and chambers (points), in relation with the average rate of the separate systems of the urban basins.

### 3.2. Development of the wastewater network

Figure 7 shows the filling rate of the pipe network for a rainfall event with a 5 years return period, for a scenario considering the population growth situation in 2040. The figure shows that capacity limitations are observed, but that no critical problems have to be expected.

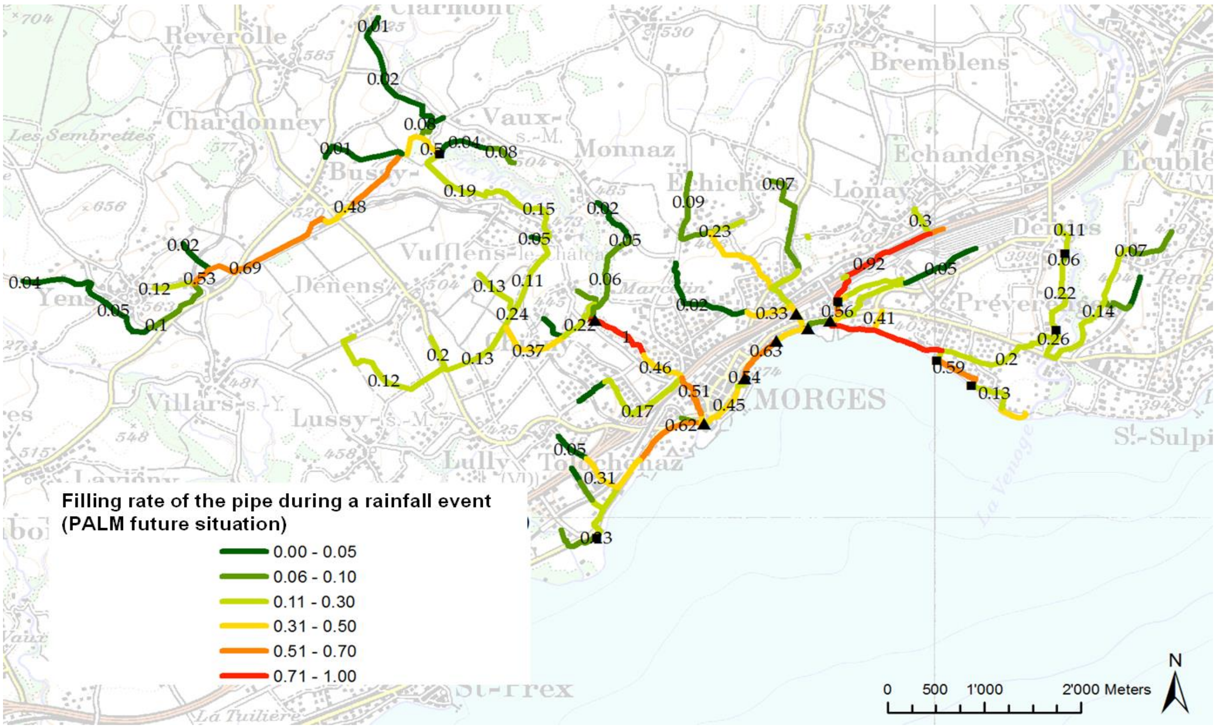


Figure 7: Filling rate of the wastewater network during a 5 years return period rainfall event, situation in 2040.

However, the detailed analysis of this situation shows that new extensions of the wastewater network are only possible with an increase of the hydraulic capacity. Extensions alone would lead to an increase of the spillovers into the natural river network by a factor 10.

## 4. REAL-TIME FORECASTING INFORMATION SYSTEM

### 4.1. Introduction

In the future, real-time forecast information will enhance optimal decision-making by integrating a better knowledge of the spatial variability of the processes. Dealing with the urban drainage networks management, online forecast systems can tackle several problems:

- Floodings by heavy precipitation can cause severe damages in urban areas. Forecasting information supports protection measures, such as emergency plans of city authorities, or warning affected people.
- Some maintenance works in the wastewater network have to be realized with low flow conditions. A forecasting system allows determining the best moment for such projects or measurements campaigns. Moreover, the efficiency of the treatment plant can strongly be improved by optimizing some processes based on predictive information of inflow, temperature and pollutant concentration.
- New infiltration or leakages, new contributors can lead to an overload of the wastewater network or to dysfunctioning of the treatment plant or pumping stations. These effects can be detected by comparing theoretical simulated and measured flows. As an example, when differences between simulated and measured flows occur and cannot be easily explained by the assumptions of the model, they may highlight changes in the flow contribution.
- Insufficient knowledge of the drainage networks may lead to poorly allocated investments for network rehabilitation or enhancement. In this case, the use of a monitoring system allows the daily verification of the assumptions produced in the forecast model. This long-term process slowly leads to a very deep knowledge of the functioning of the drainage system and to an optimal maintenance and adaptation strategy.

### 4.2. Model transformation

In the following part the transformation of the RS2012-City simulation model into a real-time forecast information system is presented. The data processing of the real-time forecast information system is presented in Figure 8.

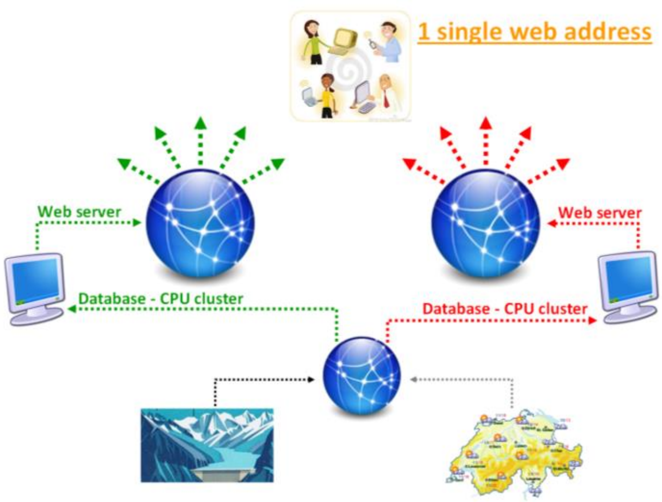


Figure 8: Data processing of the real-time forecast information system (process flow from bottom to top).

The real-time data is issued from numerical weather models, weather and discharge gauging stations, as well as other data sources such as pipe network and treatment plant measurements. This data is stored in a central SQL database. The data is then processed by the RS2012-City simulation model and the results are disseminated in a web platform. Two redundant data processing systems, including data acquisition and storage, data processing and data dissemination, are operated.

The simulations of the last 24 hours as well as the forecasts for the next 72 hours are updated every hour and the results are presented at hourly time steps. All past simulations and forecasts are stored in the webGIS database and can be accessed by the online geographical interface. Figure 9 and Figure 10 show the situation of the basin on the 27th of June 2014, two days before a heavy rainfall event. The geographical interface identifies four critical spots: two storm spillovers one chamber to be overflown, and the inlet of the treatment plant, where the discharge reaches a critical alert level. In this situation, a flooding risk is expected in the northeastern part of the basin.

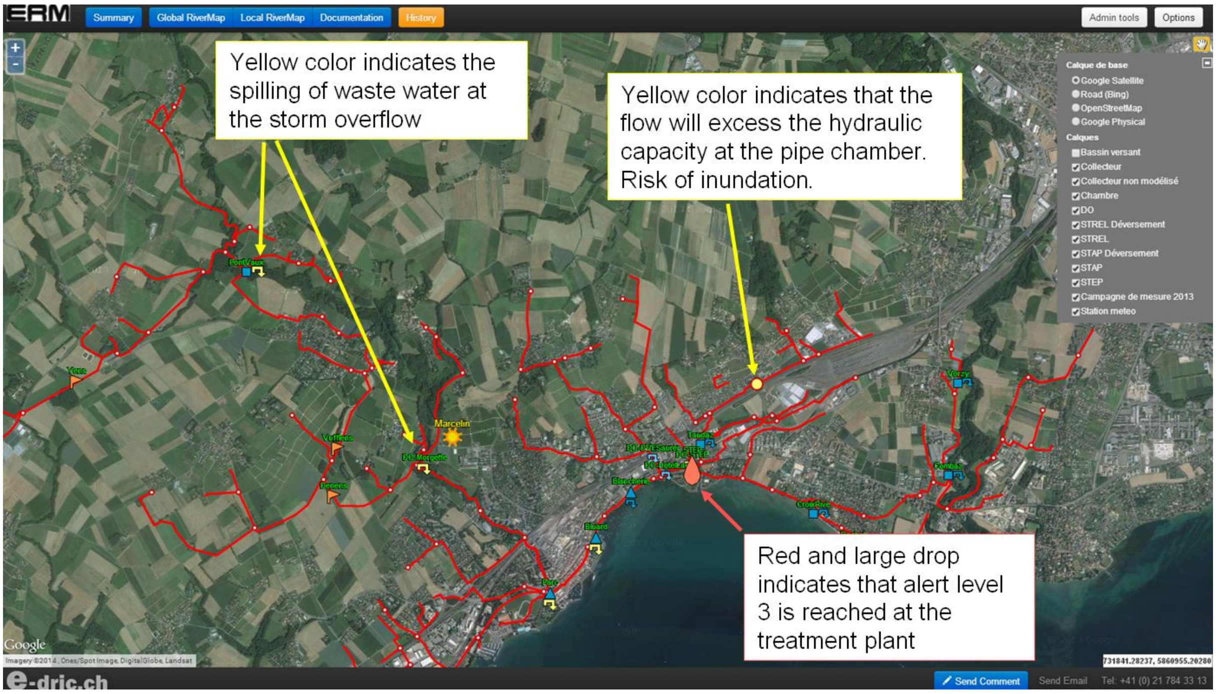


Figure 9: Online geographical interface showing the situation of the June 27th 2014, prior to a heavy rainfall event. The interface shows that 3 critical spots are expected: two of them are the spillovers of wastewater at the storm overflows and one of them is the reaching of the alert level 3 at the inlet of the treatment plant.

The forecast computed on the 27th of June at 6 am is compared to the measurement at the treatment plant (Figure 10). The figure shows the total inflow as well as the contribution of wastewater and rain water. The rainfall is occurring 48 hours after the forecast dissemination: in this example, the quality of the forecast is excellent and the timing as well as the amplitude of the inflows are correctly predicted.

The city of Morges is currently using the real-time forecast system to improve its knowledge on the system, to help defining substantial investments for the maintenance and adaptation of the wastewater network. Moreover, the prediction of spilling at the storm overflows and pumping stations is used in order to check the impacts of such wastewater releases to the environment.

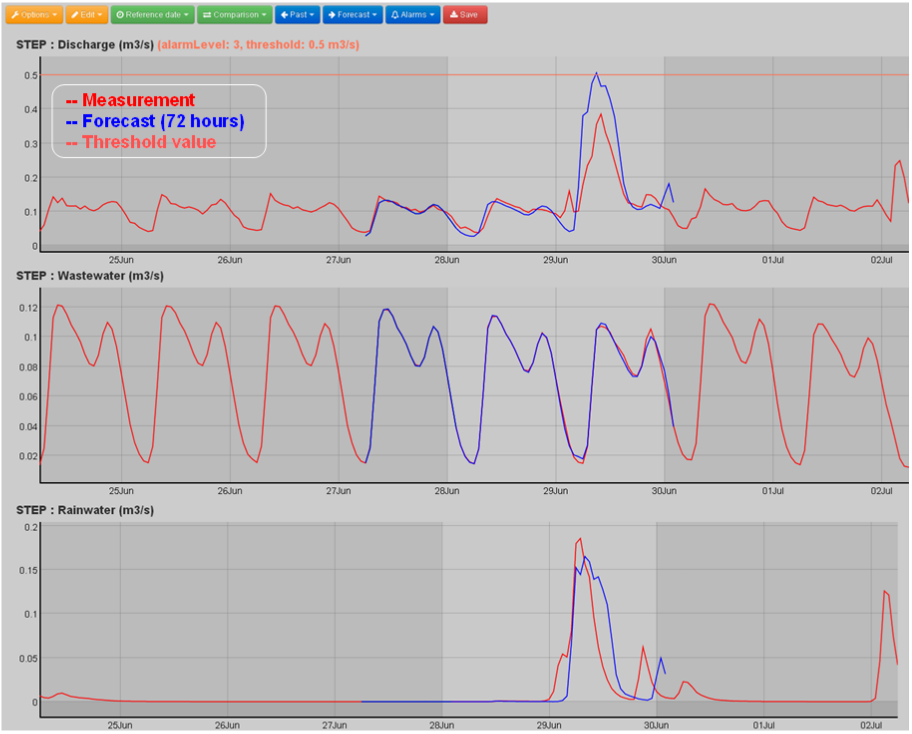


Figure 10: Presentation of inflows in the treatment plant for the forecast of the 27$^{th}$ of June 2014. The total discharge (top), the contribution of wastewater (middle) and the contribution of rain water (down) entering the treatment plant is shown. In blue: forecast; in red: measurement (note that "measurements" of wastewater and rain water contribution are simulated values based on observed weather input data).

## 5. CONCLUSION

This paper presents the analysis of the wastewater network of the city of Morges in Switzerland, as well as the development of the real-time forecast system used to manage this complex urban basin. Due to significant population growth in the past and the future, a suitable strategy of maintenance and adaptation of the wastewater and stormwater drainage networks has to be realized. In order to support decision-making for substantial investments, a detailed and prospective analysis of the wastewater network has been conducted, based on rainfall-runoff simulation.

The development of the rainfall-runoff model is based on the RS2012-City technology, which is able to fully couple hydrological processes with hydraulic functions such as river and reservoir routing or water allocation. After a intense calibration and validation process, the reliability of the model has been assessed and taken as a reference for the analysis.

The main results of the analysis reveal that the future development of the wastewater network will imply new investments in order to maintain the negative impacts of wastewater drainage and treatment to the current level. In fact, the results indicate that no significant problems are expected during dry periods, but overflows at storm spillovers and pumping stations are expected after the extension of the network. In order to avoid this increase of wastewater overflow to the environment, a combination of solutions such as minimization of continuous groundwater infiltration, reduction of the areas with combined system as well as the extension of hydraulic capacity will allow a sustainable development of the region.

Finally, the simulation model has been transformed into a real-time forecast system detecting the inflows into the wastewater network and the natural river network. The advantages of this model are the possibility to enhance the emergency planning of the city, including the early warning system. The model can also enhance the knowledge of sewer operators on the drainage networks by comparing the prediction and the measurement, optimize operation and planning of field surveys, and finally allow the optimization of the wastewater treatment thank to the quantitative inflow forecast up to 72 hours ahead.

## AKNOWLEDGEMENTS

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