A NUMERICAL AND EXPERIMENTAL MODEL OF AN URBAN CATCHMENT IN THE NORTH OF SPAIN: PARAMETER FITTING AND AN ANALYSIS OF ITS BEHAVIOUR

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ABSTRACT

Santiago de Compostela is a cosmopolitan European city that is known world-wide as one of the most important destinations for thousands of catholic pilgrims who flock there every year. It is also the capital of the Autonomous Community of Galicia and has a population which has burgeoned, especially during the last decade, ever since it became the seat of the government. For these reasons, in addition to its being one of the rainiest cities in Europe, the existing drainage system has become insufficient, and as a result, the main receiving system, the river Sar, is completely degraded and has turned into one of the most polluted in Galicia.
This paper presents a methodology for the hydrological study of a catchment, based on the utilisation of a numerical model (SWMM) for the simulation and analysis of its behaviour, as well as on the development of an autocalibration process with a non-linear parameter estimator tool (PEST). A pilot catchment, called "El Ensanche" (45 hectares) is studied with the methodology that was developed and the most relevant results are presented and discussed.

KEYWORDS

Urban drainage; modeling; SWMM; calibration; non linear parameter estimation; PEST.

INTRODUCTION

The aim of this paper is to present part of the global Project for Santiago de Compostela´s drainage system, based on high environmental criteria and hydrocomputerized tools in order to reduce the environmental impact of the drainage system on the receiving one.

The current system consists of the urban sewer network, the two main sewers Sar and Sarela that lead to the wastewater treatment plant in Silvouta, and the rivers Sar and Sarela (tributary of the Sar) as the water receiving system. The arrangement of these elements can be seen in Figure 1 as well as the representation of the urban catchment studied "El Ensanche" in Figure 2.

The final goal is to attain pre-established quality standards for the rivers Sar and Sarela, both for steady low level exposure (A2 of Directive 75/440 EEC) and for short term CSO episodes of pollution.

In order to achieve these objectives, we have established a methodology based on continuous hydrological and quality modeling, in order to provide a hydrodynamic description of flows and pollutants in the system and finally come up with the necessary procedures that will guarantee the above-mentioned quality standards.

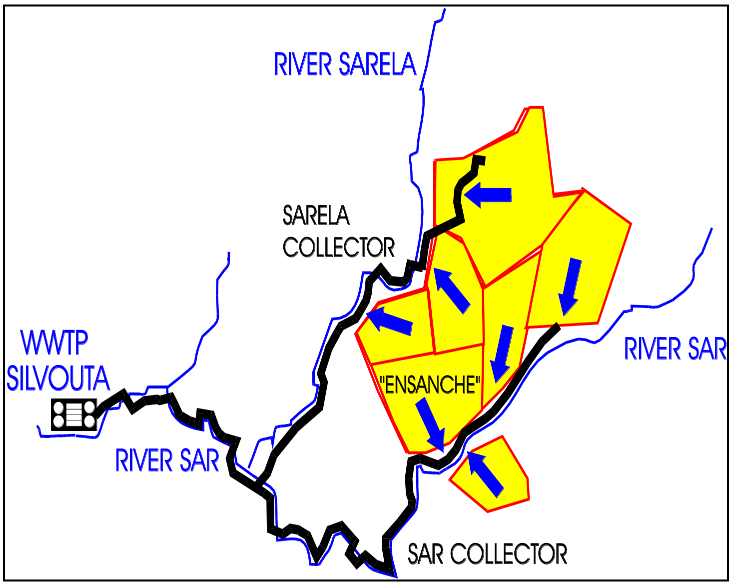

Figure1. Sketch of the draining system of Santiago de Compostela

Figure 2. The catchment studied "El Ensanche"

These procedures will be considered as the fundamentals for a Master Plan of Santiago de Compostela´s Drainage System, whose basic steps are:

(1) A detailed analysis of the existing system (sewer network, main collectors, waste water treatment plant and the receiving waters).
(2) Definition of objectives to achieve (quality standards in receiving waters and optimisation of the drainage system).
(3) Defining remedial measures (design of stormwater impoundments such as detention basins, underground impoundments, etc.) to improve the operation of the system and to achieve the standards for the protection of receiving waters and the environment during dry and wet weather.
(4) Re-definition of the future wastewater treatment plant of Silvouta.
(5) Establishment of a real time control and management system.
(6) Finance program

The aim of this paper, which is to present the process of modeling and calibration of one of the subcatchments known as "Ensanche" (Figure1) as well as the most relevant outcomes of this process, will contribute to the definition of the Master Plan mentioned above.

THE PROBLEMS WITH SANTIAGO DE COMPOSTELA´S DRAINAGE SYSTEM

Santiago de Compostela is the capital of the Autonomous Community of Galicia and it is known worldwide as the destination of thousands of catholic pilgrims every year. It has a population of about 100.000 which is still growing. As we mentioned above, the city lies between the rivers Sar and Sarela, the latter is an affluent of the former.

The sewer network is totally combined except for the subcatchment of "Fontiñas" which has a separate system. As we can see from Figure 1, there are a total of seven subcatchments draining either into the Sar Collector or to the Sarela Collector. These two collectors run parallel to their corresponding rivers and they join downstream before reaching the wastewater treatment plant in Silvouta.

The problems of the existing system are:

(1) Old and leaking sewers built at different times with different materials and various non-standard shapes.
(2) Local flooding and drainage problems in the city of Santiago de Compostela.
(3) Very high rates of infiltration flows such as groundwaters and uncontrolled pumping waters.
(4) Frequent combined sewer overflows to the rivers Sar and Sarela due to heavy rainfall (1.500 mm/year), which means very high rates of pollutant discharges to the receiving system.
(5) An under-sized wastewater treatment plant that barely has the capacity to treat dry weather flows, so the quality of the effluent is quite poor every time that a rainfall event occurs.
(6) The river Sar carries near 500 litres/sec during the summer time and the average for the plant effluent´s flow is nearly 400 litres/sec. As can be imagined, the plant´s effluent is thoroughly conditioning the water quality of the river Sar downstream from the treatment plant.

Finally, and as a result of the above-mentioned issues, the combination of points (4),(5) and (6) has lead to the degradation of the environment of the river Sar.

METHODOLOGY

In order to achieve the optimisation of the entire drainage system for Santiago de Compostela, the first step is to develop a drainage model for each of the seven catchments involved. According to this, the first phase was the modeling and further calibration of the catchment “Ensanche”, which are processes that establish the methodology for the rest of catchments using simulation and autocalibration tools.

Modeling

This first phase has been developed through the implementation of the Storm Water Management Model (SWMM) from the Environmnetal Protection Agency (EPA) of the United States of America.

The sequence of activities included the following:

Activity 1.-Data collection, systematization and preparation of the input to the numerical model SWMM

The data collected were:

(1) topographic information on the urban catchment and pluviometry information in the form of rainfall hietographs for the runoff simulation;
(2) information on the sewer network for the unsteady flow routing model.
(3) information of population and water consumption in order to estimate the base flow and infiltration rates.

Activity 2.-Development of the hydrological model

The drainage basin has been conceptually represented by a network of hydraulic elements: subcatchments (discretization of the catchment), channels and pipes. The first two first elements have been used to simulate the quantity of urban storm water runoff for different rain events, while pipes and manholes represent the closed conduit system that routes inflow hydrographs of rainfall and base flow (wastewaters and infiltration) down to the outfall of the catchment.

Calibration

The simulated hydrographs from the Stormwater Management Model are compared to measured hydrographs at the outfall point of the catchment. This second phase has been developed with a numerical model called PEST 98 which stands for Parameter Estimation.

This involved the installation of a control section over the conduit at the outfall of the catchment. Water level and the velocity are recorded in order to calculate the output hydrographs, which are introduced to PEST 98 as the "*observations*" to an observation file, together with the template file where the "*parameters*" to be calibrated are set, and the instruction file where PEST 98 is linked with the physical model SWMM as well as where certain variables are set to make sure that the calibration process is successful.

MORPHOLOGY OF THE STUDIED CATCHMENT

The catchment that has been studied, "El Ensanche", has a combined sewer system and serves nearly forty thousand people. The area covered is about forty five hectares., 100% developed and mainly used for residential purposes. The constructed area accounts for 68% of the total surface and the 32% remaining corresponds to streets and parking lots, so it is possible to assume that imperviousness is nearly 100%. In order to confirm this hypothesis, we calibrated this parameter separately and the result was an imperviousness of 94.5%.

One of the main characteristics are the steep slopes of its streets, with an average of 4.2% and a maximum of 13.3%. This fact is quite important in the behaviour of the runoff, and it has therefore been considered in the model. The effect is that there are very steep rising limbs in our hydrographs when rainfall events occur and the time it takes to reach the peak flow will range from 30 to 35 minutes.

CONCEPTUALIZATION OF THE CATCHMENT

As mentioned earlier, the Storm Water Management Model (SWMM) has been used to simulate the urban storm water runoff over our catchment during rainfall events (RUNOFF block) as well as the routing of the inflow hydrographs due to runoff, wastewaters and infiltration through the existing sewer network down to the outfall of the catchment (EXTRAN block).

The RUNOFF Block generates surface runoff in response to precipitation and the key to applying RUNOFF is the division of the catchment into a number of subcatchments. Each subcatchment should be relatively homogeneous (i.e.,the physical characteristics such as slope, roughness, imperviousness, ...,should be consistent). In this way, we divided our catchment into a total of 231 subcatchments: 85 corresponding to streets, and 146 corresponding to roofs. The representation of the discretization of the catchment is shown in Figure 3.

The conceptual view of surface runoff used by the Runoff block is that each subcatchment surface is treated as a nonlinear reservoir with a single inflow, precipitation. There are several discharges including infiltration, evaporation and of course runoff. The capacity of this reservoir is the maximum depression storage, which is the maximum surface storage provided by ponding, surface wetting and interception. Surface runoff occurs only when the depth of water in the reservoir exceeds the maximum depression storage. So, the precipitation intensity less the rates of infiltration and evaporation is the net inflow to the resorvoir. The entire process is repeated for each subcatchment and is modeled by two equations: (1) continuity equation, which keeps track of the volume or depth of water on the surface of the subcatchment; (2) Manning´s equation to model the rate of surface runoff as a function of the depth of flow above the maximum depression storage depth (Nix,1994).

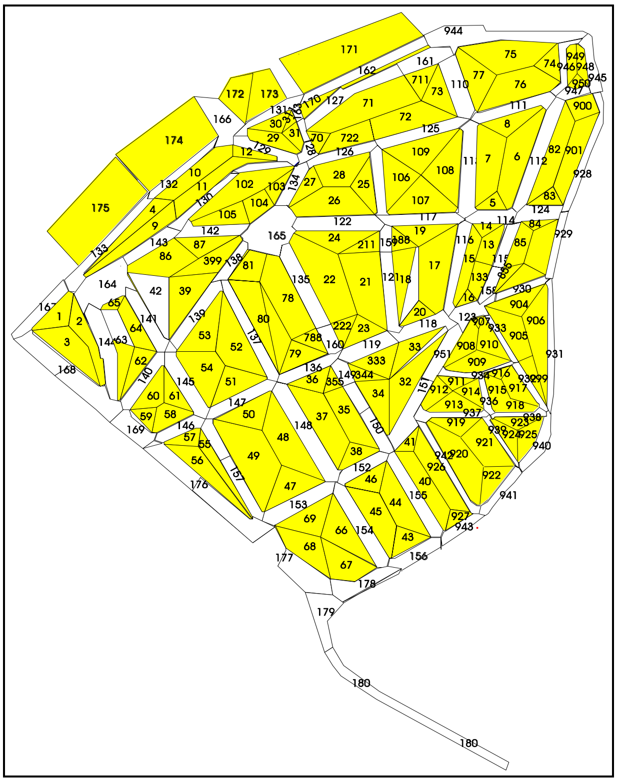

Figure 3. Discretization of “El Ensanche” RUNOFF block

The roofs drain to what we call channels, which represent the drainage conduits that carry the generated runoff to an inlet of the sewer network or main net. Streets drain directly to an inlet of the sewer network located at intersections. This is a good approach because a very high rate of storm water doesn´t go into street inlets due to the steep slopes; instead, it goes into inlets at intersections because they are flat. We have introduced 84 channels which are called the secondary net. A representation can be seen in Figure 4.

The secondary net is simulated in RUNOFF, while the main one is simulated in EXTRAN.

The extended transport block (EXTRAN) is a dynamic flow routing model that routes inflow hydrographs through an open channel and/or closed conduit system, computing the time history of flows and heads throughout the system (Roesner et al.,1992). The program uses the complete Saint-Venant equations with an explicit solution technique to step foward in time.

The conceptual representation of the sewer network is based on the “link-node” concept so that links (pipes) transmit flow from node to node. Nodes are the storage elements of the system and correspond to manholes or pipe junctions in the physical system. We have modelized 169 pipes and 167 manholes, which represent what we call the main net. A sketch of the principle net is shown in Figure 5.

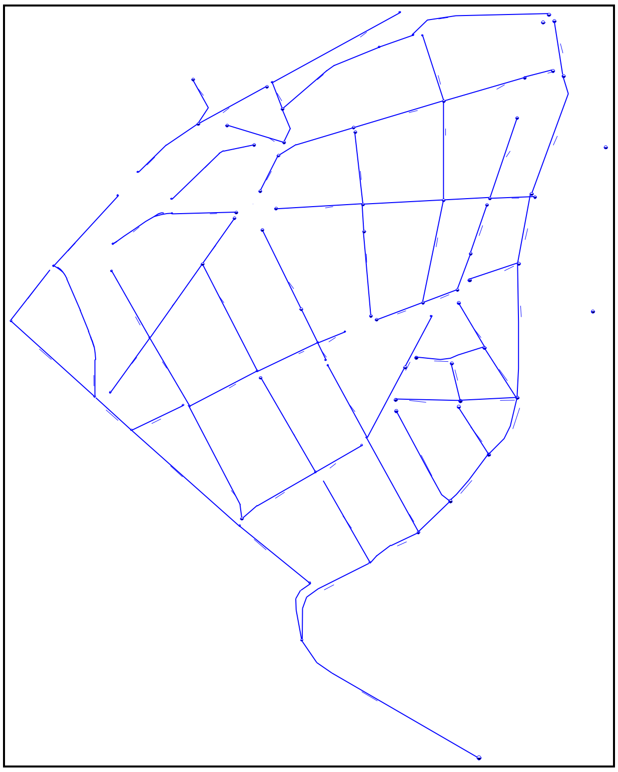

Figure 4. Secondary net (channels) RUNOFF block

So in the end, what we have is a simulated hydrograph at the outfall of the catchment for the rainfall history that has been registered and introduced to the model. The next step is to calibrate de model by comparing simulated hydrographs to those that have been recorded at the control section.

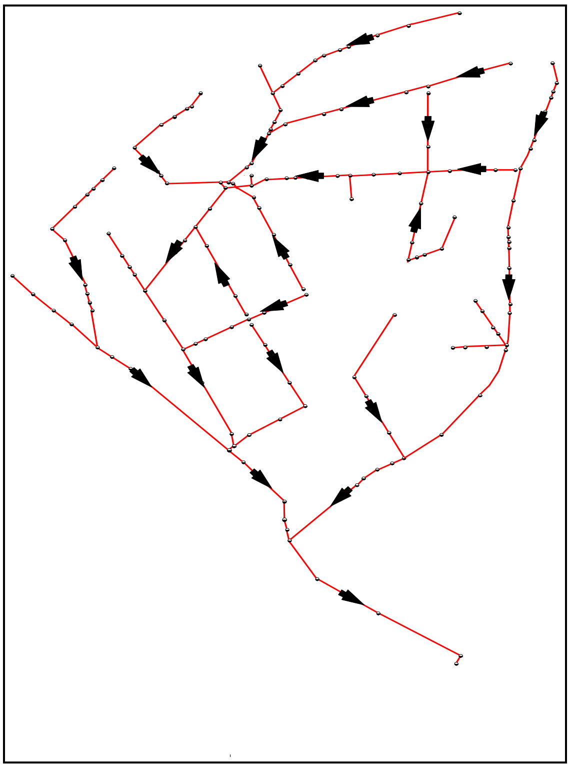

Figure 5. Main net (pipes and junctions). EXTRAN block

MODEL SIMULATION AND CALIBRATION

Introduction

Due to the need to assign some measure of objectivity and confidence to the model´s predictions and because of the uncertainty of certain parameter values in the model, we decided to develop an automatic calibration with a specific software package called PEST, which stands for Parameter Estimation.

It is important to note that automatic methods such as an autocalibration process require user expertise and that allowable ranges on the parameters that are being calibrated must be known because a possible failure in the optimization process might occur.

An automatic parameter estimation procedure consists of four major elements: (1) an objective function; (2) the optimization algorithm; (3) the termination criteria, and (4) calibration data.

An objective function is an equation that is used to compute a numerical measure of the difference between the model-simulated output (hydrograph at the outfall) and the observed watershed output. The aim of the autocalibration process is to find those values of the selected model parameters that optimize (minimize) the numerical value of the objective function.

PEST uses the Weighted Least Squares (WLS) function:

$$F(\theta) = \sum_{t=1}^{n} \omega_t \cdot \left[q_t^{obs} - q_t(\theta) \right]^2$$

where:

q_t^{obs} = observed (measured) flow value at time t

$q_t(\theta)$ = model simulated flow value at time t

θ = vector of model parameters

ω_t = weight at time t

n = the number of data points to match

The surface described by the objective function in the parameter space is called a “response surface”. An optimization algorithm is a logical procedure that is used to search the response surface, restricted to the allowable ranges on the parameters, for the parameter values that optimize the numerical value of the objective function (Sorooshian and Gupta, 1995).

PEST uses the “Gauss-Marquardt-Levenberg algorithm”. The purpose of this paper is not to discuss this algorithm, but we will briefly comment on how the optimisation process is developed. For nonlinear problems, parameter estimation is an iterative process. At the beginning of each iteration the relationship between model parameters and model-generated observations is linearised by formulating it as a Taylor expansion about the currently best parameter set; hence the derivatives of all observations with respect to all parameters must be calculated. This linearised problem is then solved for a better parameter set, and the new parameters tested by running the model again. By comparing parameter changes and objective function improvement achieved through the current iteration with those achieved in previous iterations, the program can tell whether it is worth undertaking another optimisation iteration;if so, the whole process is repeated.

Derivatives of observations with respect to parameters are calculated using finite differences with the method of “foward differences”.

Continous dynamic simulation

Figure 6 shows the recorded hydrograph that has been used to simulate and calibrate the model together with the hietograph that causes it.

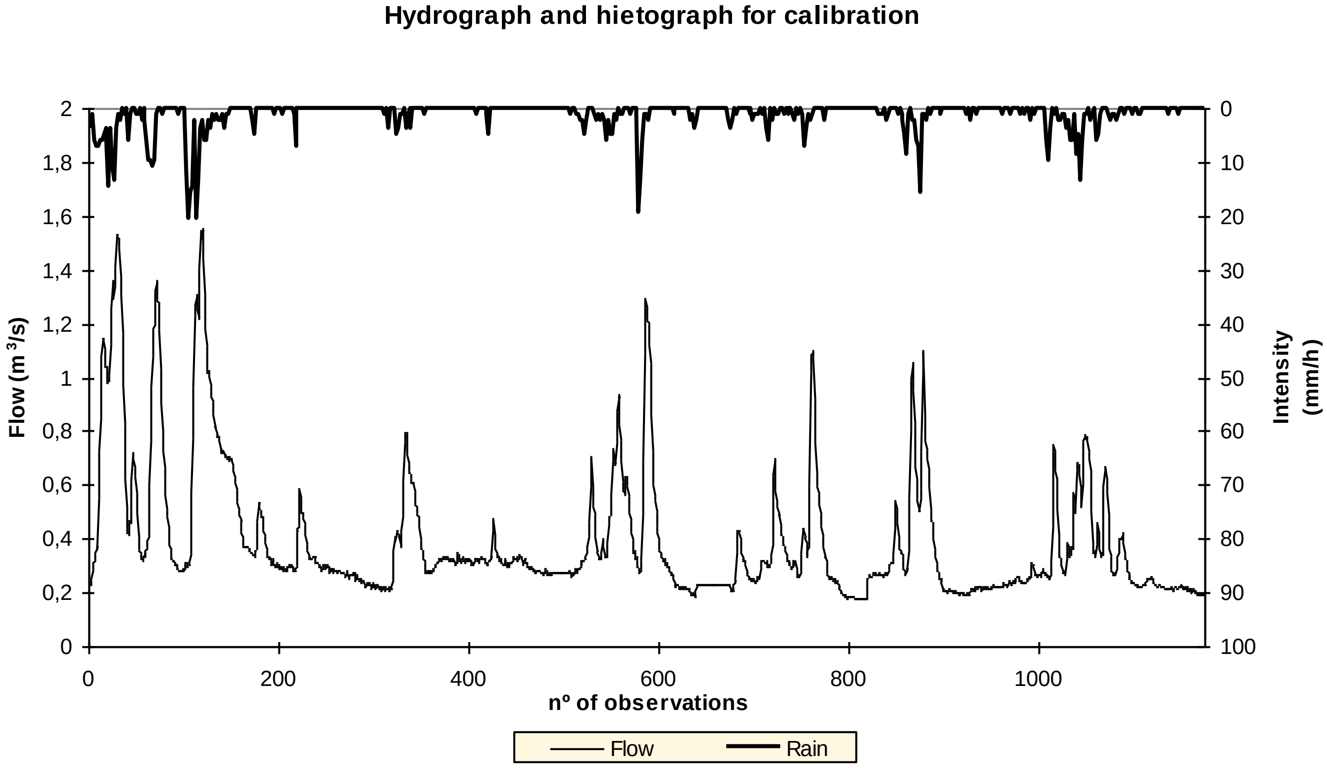

Figure 6. Hydrograph used for calibration.

This hydrograph is the result of a combination of five storm events occuring between the 16th of September and the 14th of October 1996. The total length of simulation is 99 hours and a minimum inter-event time of three hours with no precipitation has been set so that the drainage system can re-establish base-flow functioning before the next storm event. The aim of putting these hydrographs all together is to achieve a representative set of calibrated parameters for the catchment “El Ensanche” and not only for each individual storm event. One problem associated to the combination mentioned above is the variation in the base flow between events. In order to achieve some knowledge about the behaviour of the base flow, an analysis has been developed as it can be seen in Figure 7.

Figure 7 represents the base flow of an entire day of November 97 against one of February 98. A concluding remark from Figure 7 is the high infiltration rate (a variable, whose mean value is about 200 litres/sec) to our sewer system. This is based on the lack of correlation between the recorded base flow and an expected base flow of about 150 litres/sec**.** This error will have a certain influence on the accuracy of the calibration process that is presented below.

One of the future developments is to delimit physically the sources of the infiltration waters into the catchment “El Ensanche”.

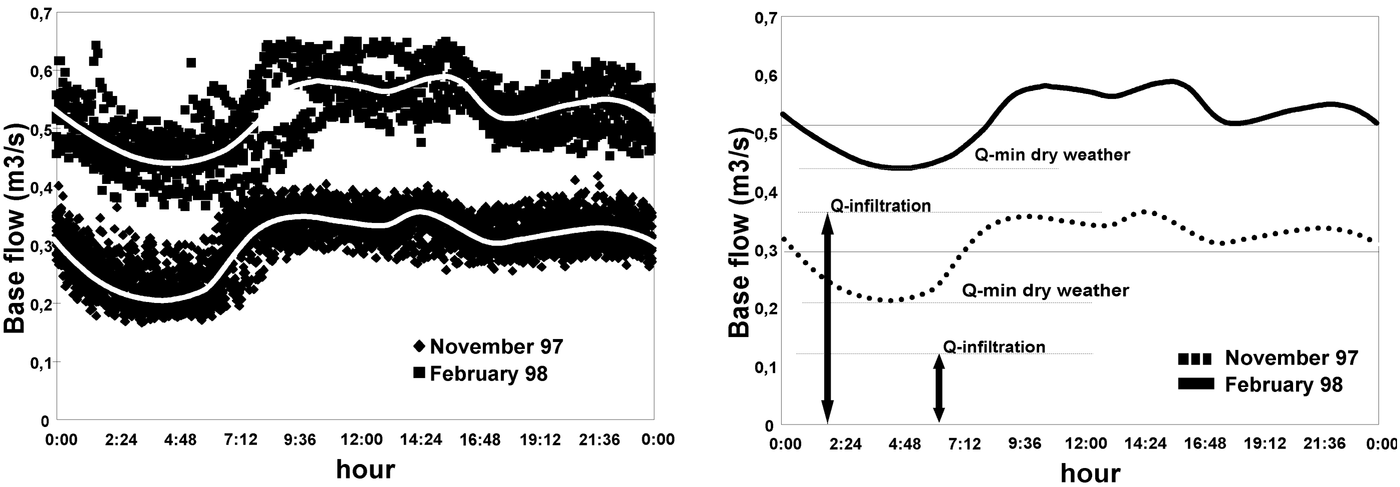

Figure 7. Variable base flow of the “Ensanche”

PEST calibration of the catchment studied

The criteria used in the selection of the parameters to be calibrated were based on the combination of:

(1) parameters with no site-information.
(2) high grade of difficulty and/or a great amount of time-consuming work for their estimation in the real watershed.
(3) parameters that are not bound to be correlated in order to increase the reliability of the predictions of a successful calibration process.

According to the third statement, a first set of six parameters (1.-Manning´s roughness coefficient of channels and pipes, *ncnd* ; 2.- Manning´s roughness coefficient of streets, *ncll* ; 3.- Manning´s roughness coefficient of roofs, *ntej* ; 4.- Equivalent slope of roof surfaces, ptej ; 5.- Depression storage of streets, *retecll* and 6.- Depression storage of roof surfaces, *retetej*) was selected in order to be calibrated. On analysing the Covariance and Correlation Coefficient Matrixes, a high correlation between certain combinations of parameters was found. These combinations correspond to: 4-6, 4-3 and 2-5, therefore, they cannot remain together in the same calibration performance. According to this, the following sets of non-correlated parameters shown in tables 1 and 2 were considered:

Table 1 - Set 1

Parameter	Seed	Lower bound	Upper bound
ncnd	0.018	1.00 E-02	3.00 E-02
ncll	0.020	1.00 E-02	4.00E-02
ptej	0.00016	1.00 E-06	1.00 E-02

Table 2 - Set 2

Parameter	Seed	Lower bound	Upper bound
ncnd	0.017	1.00 E-02	3.00 E-02
ntej	0.014	1.00 E-02	3.00 E-02
retecll	1.00	0.20	2.50
retetej	1.00	0.25	2.50

It is necessary to point out that the "Equivalent slope of roof surfaces" (*ptej*) is a fictitious parameter. By this we mean that the physical process that we are modeling includes the runoff over the roof surface and the drainage alongside the gutters of the roof before it enters the rainwater pipe that leads down to the conduit under the street; the conceptualization of this same process in the model is much simpler as explained in Conceptualization of the Catchment.

Results of the calibration

The calibration results are shown in tables 3 and 4:

Table 3 - Set 1

Parameter	Estimated value	95% percent confidence limits	
		Lower value	Upper value
ncnd	0.024	2.28 E-02	2.56 E-02
ncll	0.026	1.63 E-02	3.67 E-02
ptej	0.00027	2.23 E-04	3.18 E-04

Sum of squared weighted residuals = 18.22

Table 4 - Set 2

Parameter	Estimated value	95% percent confidence limits	
		Lower value	Upper value
ncnd	0.023	2.13 E-02	2.54 E-02
ntej	0.018	1.61 E-02	2.09 E-02
retecll	0.630	0.24	1.51
retetej	0.950	0.58	1.31

Sum of squared weighted residuals = 18.67

As can be observed from tables 3 and 4, 95% percent confidence limits are quite good for the adjusted parameters which implies the following: (1) there is a high level of certainty in the estimation of parameter values; (2) all of the selected parameters correlate poorly to each other.

The set of parameters from table 3 has been chosen due to its lowest sum of squared weighted residuals. We are aware that the calibration results for each set of parameters depends on the values established for the fixed parameters. Therefore, the physical sense is partially lost in order to reproduce the recorded hydrograph at our control section (Fig.6).

Figure 8 shows the hydrograph that has been recorded at our control section plotted against the simulated one using set 1 of calibrated parameters .

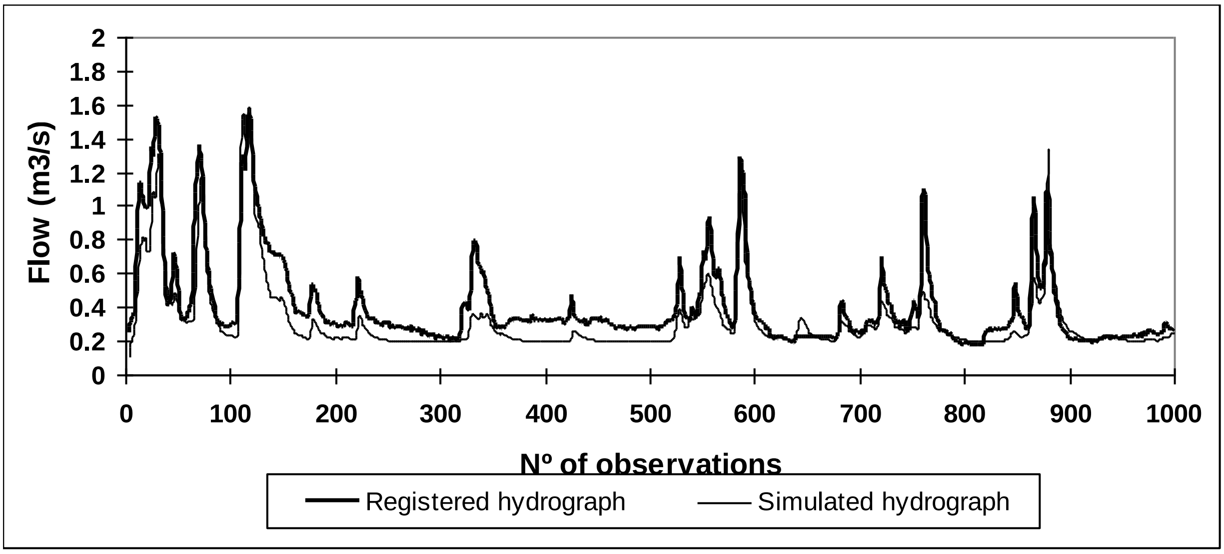

Figure 8. Registered and simulated hydrographs

Total volume of the recorded hydrograph = 121747 m^3
Total volume of the simulated hydrograph = 97105 m^3
Error = 20%

Although this error is relatively important (about 80 l/sec average), it is mainly due to the lack of similarity between the base flow of the recorded hydrograph and that of the simulated one, as we can see from the above figure as well as in Figure 7. The reason that may explain this fact is that we are simulating the base flow as a constant inflow to the network at nodes in the EXTRAN block, thus we do not reproduce the seasonal and hourly variations as occur in reality.

It is important to point out that the same events have been simulated individually (each with its own base flow) with their own calibrated parameters and we have attained errors between recorded and simulated volumes ranging from 3 to 7%, which are quite reasonable. Obviously, the set of calibrated parameters of each individual case are different.

CONCLUSIONS

The main conclusions of this study are:

- A general methodology for the hydrological study of a catchment based on a simulation and further parameter autocalibration processes have been developed and particularized for the catchment "El Ensanche"of Santiago de Compostela, attaining quite good results in the simulation of its behaviour.

- The autocalibration process was developed using a non linear parameter estimation tool called PEST98, which stands for Parameter Estimation. This process has shown that certain parameters are highy correlated and cannot be considered in the same calibration performance.Therefore, calibration results depend on the values of fixed parameters and as a result, physical sense is partially lost in order to reproduce the recorded hydrograph at the control section of the catchment studied.

- From the analysis of the recorded hydrographs at the control section and the expected wastewater flow of the catchment studied, we may point out a very high rate of infiltration to the sewer network of the "Ensanche" catchment. This infiltration flow varies quite significantly throughout the year depending on preceding weather conditions as well as on the season of the year. Also, due to the fact that the variable base flow had to be introduced into the model as a constant inflow, which is quite significant, some accuracy is lost in the performance of the hydraulic simulation of the drainage system which will obviously have an effect on calibration results.

- Despite the lack of accuracy between the recorded and the simulated data, the methodology developed seems to be reliable. A set of non correlated parameters has been defined and will be used to improve the calibration of this catchment and to calibrate the rest of the catchments of the drainage system of Santiago de Compostela.

ACKNOWLEDGEMENTS

The authors thank the City Hall of Santiago de Compostela, AQUAGEST Galicia, S.A., and the CICYT (project AMB95-0997-CO2) for their helpful cooperation which improved the contents of this paper.

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