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Design of a conceptual model of suspended sediments with validation on sewage-system data from ten urban catchments

Conception et validation d'un modèle conceptuel de matières en suspension sur dix bassins versants urbains

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RESUME

Les matières en suspension (MES) peuvent être considérées comme les principaux vecteurs et *traceurs* de la pollution des rejets urbains par temps de pluie (RUTP) car de nombreux polluants, notamment les métaux lourds, sont absorbés par les particules organiques ou minérales entraînées par les eaux pluviales.

Nous proposons une modélisation de la concentration et des flux des MES à l'exutoire d'un bassin versant urbain ou d'un réseau d'assainissement, en choisissant le calage des états initiaux dans la simulation événementielle. Les modèles utilisés pour la modélisation hydraulique et qualitative sont des modèles conceptuels globaux qui nécessitent pour leur calage un nombre limité de données et sont économes en paramètres. La base de données comprenant plusieurs bassins urbains, nous a permis des estimations de paramètres robustes et la validation du modèle des MES.

ABSTRACT

Suspended sediments (SS) may be considered as the principle vectors and *tracers* of pollution in wet-weather urban runoff because many pollutants, and heavy metals in particular, are absorbed by the organic or mineral particles carried by rainwater.

We propose a model of SS concentration and fluxes at the outlets of urban catchments or sewer systems, with calibration of the initial state parameters in the event simulation. The models used for the hydraulic and qualitative modeling are comprehensive conceptual models that require a limited number of data for their calibration and have few parameters. As the database included several urban catchments, we were able to make robust parameter estimates and validate the SS model.

KEYWORDS

Model conceptual ; model calibration ; validation ; sewage systems ; suspended sediments.

1 INTRODUCTION

1.1 Context of the study

Currently, within the context of environmental concerns, there is increasing awareness of the importance of the pollution that is carried by runoff and discharged directly into the natural environment. This pollution occurs during ordinary rain events, and its impact increases with the intensity of the rainfall. The French decree dated 22 December 1994, regarding monitoring of wastewater collection and treatment facilities, imposes an estimation of discharged volumes and masses and recommends the use of measuring equipment to estimate the volume loads and mass loads of the suspended sediments (SS) discharged into the receiving environment during rain events. However, monitoring systems and maintenance of the sensors are very costly. Within this context, as the regulations do not impose which means must be used to estimate the pollution load, some authors (Musso, 1997; Cabane, 2001; Rossi et al., 2005) suggest estimating wet-weather urban runoff with tools that combine metrology with modeling. However, studies (Kanson, 2004) focusing on the uncertainties in the parameters and responses of the pollution flux models frequently used in software such as CANOE, Hydroworks, SWMM, MouseTrap, FLUPOL and HORUS reveal that the predictive power and efficiency of these models in producing pollutographs is still limited. Furthermore, a study (Cabane et al., 2002) on the use of pollution flux models in France demonstrates that these models are still not frequently utilized by engineering firms. Thus, the insufficiency of experimental data required for calibrating a complex model, plus our limited knowledge of the processes at play, currently seem to be the principal cause of difficulty in the use of pollution flux models for evaluating wet-weather urban runoff.

1.2 Objectives of the study

The objective of this study is to use modeling and limited data to develop a tool capable of satisfactorily evaluating wet-weather urban runoff, which is inexpensive, easy to use and apply, and provides results at least comparable to those obtained using more complex models in certain fields of application.

We propose modeling the concentration and flux of suspended sediments at the outlets of urban catchments or sewer systems, with calibration of the initial state parameters in the event simulation. The models utilized for the hydraulic and qualitative modeling are comprehensive conceptual models characterized by a small number of parameters and requiring a limited number of data for calibration. The use of the comprehensive approach is justified by the fact that certain phenomena involved in wet-weather urban runoff are not yet fully understood and other ones are not directly measurable, which is the case in particular for the stocks of material already present at the beginning of a rain event and for the SS that reenter circulation during the rain event in the system.

2 METHODOLOGY

2.1 Choice of models and their adaptation for urban catchments

For the hydraulic and qualitative modeling, we chose models that had been validated previously in natural catchments. We adapted them for use in urban catchments, presenting an intermittent character.

For the transformation of rainfall into flow rate, we propose the GR4 model (Edijatno et al., 1999; Perrin, 2000) which has been used widely in France and is suitable for operational prediction. This modified model, which we have called GR(3)mn, remains

a simple model, requiring the calibration of a single parameter (initial state of the soil reservoir) and is compatible with the constraints of event modeling. It operates at short time steps (5 min), which is all the more important in the context of modeling hydrological processes in sewer systems, in particular the modeling of SS pollutographs.

For the qualitative modeling, we chose a comprehensive conceptual model with four parameters. Analysis of the various configurations of the model's parameters and of the sensitivity of the parameters led us to modify this initial model, to make its structure simpler and reduce the number of parameters to three.

$$\frac{dS}{dt} = A_e Q^{1.8} - C Q^{1.8} S^2$$

Q (l/s) - flow rate; dt (h) - calculation time step; S (kg) - stock of SS;
parameters: A_e ((kg/h)*(s/l)^{1.8}), C ((kg⁻¹h⁻¹)*(s/l)^{1.8})

This SS model can operate at variable time steps, as well as at fixed time steps, and enables a description of the pollutographs on the scale of an event.

2.2 Database utilized

The data utilized come from the QASTOR database (Saget, 1994), which is one of the first databases concerning the quality of urban discharge, characterizing the quality of the discharges of a system in wet weather at the outlet of an urban catchment. It features measurements from long-term campaigns on various catchments and contains data that have been verified, criticized and validated. In this study, the GR(3)mn model was applied to 6 urban catchments with areas of 26 ha up to approximately 100 ha, and the SS model was applied to 11 catchments with areas of 26 ha to 1114 ha. These were 7 stormwater sewer sites, 3 stormwater sewer sites in which the presence of wastewater in dry weather conditions was observed, and 1 combined sewer site (sanitary sewer and stormwater sewer).

2.3 Definition of the initial conditions

To use the models in event mode, the initial conditions of the system have to be determined. Each of the two models selected included two initial-state parameters, which were first optimized for each event using hierarchy-based optimization; for each unique set of fixed parameters of the model for a given catchment, the initial state parameters were optimized for each episode. Next, in each model, one of the two parameters of the initial states was defined by a constant value, which was the median of the values of this parameter previously optimized for each event. The values of these fixed parameters were identical for all the catchments. Thus, each model included a single parameter to be optimized per episode and required little data for its calibration.

2.4 Calibration of the models studied

To calibrate the parameters, three optimization methods were used: the Rosenbrock method, the Simplex method (Nelder and Mead, 1965) and a method consisting in exploring the shape of the objective function's hypersurface calculated for different vectors and parameters.

This last method was developed from the Uniform Random Sampling method (Duan et al., 1992; Nascimento, 1995) (comprehensive, semi-automatic) and features the visualization of the objective function's hypersurface shape. By giving indications on the location of the surface of the objective function optimum (without actually

specifying the optimum), it makes it possible to subsequently determine the starting point of the local methods applied and also to study the sensitivity of the parameters.

In order to choose a criterion for calibrating the parameters of the models and evaluate the performance of the modeling with calibration and validation, the performance of the SS model was studied according to the six different criteria applied for the optimization: the Nash criterion (Nash, 1970); the Nash criterion calculated from the SS logarithm; the Nash criterion calculated from the square roots of the SS; criterion based on the index of agreement; the relative criterion of absolute error; the relative criterion of absolute error, transformation with a power of 1/5. The criterion selected as the objective function for calibrating the parameters and assessing the performance of the models is the Nash criterion, with the exception of the estimate of the total mass per event, which was evaluated by the absolute error criterion.

2.5 Partial validation of the models

The validation centered on application of the models based on the data that were not used during calibration of the models. However, as we used event modeling that would subsequently be integrated into a stochastic model (see section 5) for the validation method, we carried out partial calibration, of a single parameter.

3 RESULTS AND DISCUSSION

First, the parameters of the GR(3)mn model were optimized for at least 40 rainfall events per catchment. However, we checked if a very limited number of episodes (around ten) may suffice to determine the values of the parameters of the GR(3)mn model while maintaining good performance of the model. We observed that in spite of the fact that the quality of the simulation decreased slightly, it remained sufficient to enable a satisfactory estimation of the SS concentration and flux for most of the events of the various catchments. By applying the GR(3)mn model with calibration and validation, we obtained satisfactory results with the Nash criterion calculated for all the episodes of a given catchment, of approximately 90%.

The parameters of the SS model were optimized for SS concentration and flux, as a function of the flow rate observed and the flow rate modeled with the GR(3)mn model. Analysis of the sensitivity of the parameters demonstrated that parameter C of the model is not very sensitive; that one of the parameters of the initial states, "Sini" is relatively sensitive, but that it may be constant for a given catchment, because it only influences the beginning of the event. Thus, even if it is poorly estimated, the total mass per event remains well evaluated in most episodes, so that a single parameter per event is optimized. The SS model is more coherent, because the parameters of the model obtained during calibration of the SS concentration parameters enables a good estimation of the SS fluxes. Finally, it seems to be robust, because the results obtained during its validation (with optimization required for one of the three parameters for each event) for each of the 9 catchments are fully satisfactory (see table 1).

Site	Description	Surface (ha)	Nash calculated for the concentration	Nash calculated for the flux	Absolute error criterion calculated for the total mass per event
Maurepas	stormwater sewer	26,7	97 %	90 %	96 %
Ulis Nord	stormwater sewer with presence of wastewater	43,1	98 %	98 %	78 %
Aix Zup	stormwater sewer	25,6	96 %		81 %
Aix Nord	stormwater sewer	92	94 %	93 %	93 %
Marne Sainte Boudile	combined sewer	1145	70 %	89 %	89 %
Marne Chesnay	stormwater sewer with presence of wastewater	560	89 %	91 %	90 %
Marne Grammont	stormwater sewer with presence of wastewater	144	94 %	89 %	92 %
Marne Malnoue	stormwater sewer	185	89 %	96 %	72 %

Table 1 Values of the Nash criterion calculated for the concentration and the flux, values of the absolute error criterion calculated for total mass, for the 9 catchments studied with validation and with calibration of a single parameter.

Catchment no 1 Event 108
Validation of the SS concentration model. SS concentration calculated as a function of the:
A - observed flow rate (SS(Qobs)), B - calculated flow rate (SS(Qcal)) with GR(3)mn

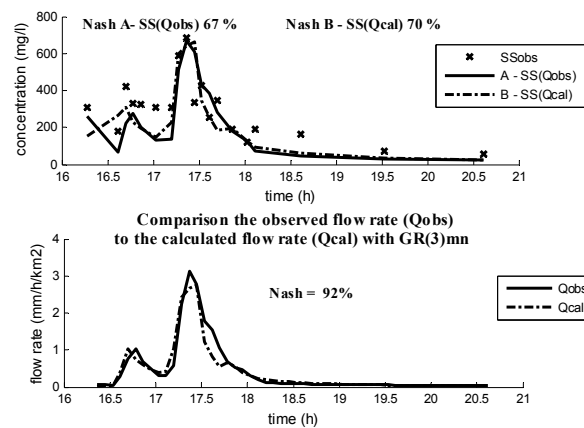


Figure 1 Adjustment of the SS concentration (top) and flow rate (bottom) with partial validation. Concentration calculated as a function of the flow rate observed and calculated with GR(3)mn.

In the application of the SS model only as a function of the observed flow rate, we obtained results higher than 80% of the Nash criterion calculated for all the episodes of a given catchment, for the concentration, and higher than 90% for the SS flux, for

all the catchments studied. The estimation of the total mass per event using the isolated concentration thus modeled also gave satisfactory results, higher than 80% for most of the catchments studied.

Figures 1 and 2 present, with the example of the modeled episode, validation results obtained for the concentration (figure 1) and for the SS flux (figure 2). On each figure, the bottom figure illustrates the flow rate calculated by the GR(3)mn model.

However, this quality decreases (while remaining acceptable) when we replace the observed flow rate comprising the input data for the SS model with the flow rate modeled with the GR(3)mn model. In fact, the simulation quality of the isolated concentrations carried out for the modeled flow rate depends significantly on the reliability of the model with which the flow rate is calculated. Regarding the estimation of the total mass per event, it is also (according to the values obtained from the absolute error criterion) sensitive to the quality of the flow rate estimation, but to a lesser degree than the SS concentration, in spite of the fact that the flow rate is taken into account at both levels of the total mass estimation: at the level of the calculation of the concentration and at that of the volume.

Thanks to the database containing data from several catchments (11), we were able to establish robust parameter estimates and obtain parameter distributions common to all the catchments and per catchment. However, the fact that one of the three parameters of the SS model must be optimized for each episode means that the model cannot be applied for forecasting.

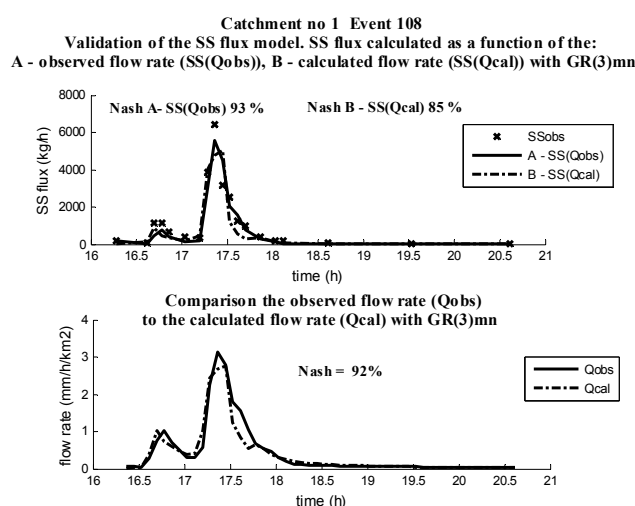


Figure 2 Adjustment of the SS fluxes (top) and of the flow rate (bottom) with partial validation. Concentration calculated as a function of the observed flow rate and calculated with GR(3)mn.

However, the model makes it possible to generate the pollutograph of the entire event from a few isolated measurements of the concentration or flux. It would be worthwhile to find out how many measurements would suffice to determine the value of this parameter, in order to satisfactorily estimate the isolated concentration during the event taken as a whole, which would make it possible to satisfactorily evaluate the total load per event.

Furthermore, for applications not focusing on individual events, but on the entire population of events, we can consider that the problem can be solved, or at least simplified, by including the full range of variability, other than that of the rain, in the distribution of the initial states of the rainfall-runoff model and of the SS model, which follow the uniform distribution law and the Weibull law, respectively.

4 CONCLUSION

While recalibration of the model at each event is acceptable for stochastic modeling, it nonetheless presents a deficiency in the comprehension of the phenomena at play. Application of the SS model reveals that it is not the initial unknown stock that is principally responsible, but rather, the influence of the flow rate, which seems to vary from one event to the next. This leads us to recommend research on the internal behavior of the solids in the system, before focusing on dry-weather phenomena.

An orientation towards continuous modeling of events would make it possible to better understand not only the issue of the initial states, but more importantly, the issue of the role played by the SS during the event, with respect to the concept of the build-up and recirculation of pollutants in the system during wet weather. Continuous studies spanning a period of at least one year would also make it possible to check if it is possible to explain the variation of parameter A_e according to seasonal changes.

We may conclude that it is necessary to pursue our efforts in terms of the reliability and availability of the data (in particular those regarding the behavior of the pollutants in the system) as well as in terms of the comprehension of the processes at play in the sewer system. Furthermore, combining modeling with measuring seems to be one of the least costly solutions for self-monitoring of systems, because it appears that with the use of a simple model, it is possible to evaluate the SS load per event with a degree of uncertainty comparable to that of complex models.

5 PERSPECTIVES

Both models presented in this paper were chosen and developed with the perspective of developing a probabilistic model of SS flux which can be implemented simply by combining GR(3)mn and SS models with a stochastic rainfall model.

Amongst all types of hydrological data, rainfall chronicles produce a more reliable statistical analysis than analysis carried out directly on flow rate, by providing useful information. Indeed, rainfall chronicles are generally longer, more independent in their successive relationships and less influenced by urban development than variables that interest managers directly, such as pollutant and SS flux.

Our idea consists of using rainfall data in the rainfall-runoff model and the SS flux model, in order to first obtain the probabilistic density function of the discharge, based on that of the rainfall, and, second, to obtain a probabilistic density function of SS flux. The rainfall may be described by the CECP stochastic model (Leviandier, 2000), which enables a breakdown of the rain episode into sub-episodes of constant intensity, simultaneously taking account of the intensity and its progression in time, in order to obtain rainfall that we call "simplified" because it is composed of four or five sub-episodes with different intervals.

This rainfall constitutes the input data for the rainfall-runoff model coupled with the SS model. The SS flow rate and flux calculated as a function of the rainfall described in this manner only depend on total rainfall, times of the iterated breakdowns, i.e. the hyetograph's shape, and the initial conditions. The shape of the rainfall (hyetograph), and consequently, the shape of the flow rate (hydrograph) are characterized by the CECP model. Thus, the probability of exceeding a certain discharge is equal to the

probability of exceeding total rainfall at a given shape, and the probability integrated for all possible shapes depends on a parameter controlling the iterated breakdowns.

Likewise, the probability of exceeding a certain pollution threshold (expressed by the flux or concentration of the SS or by the total mass of SS per event) is equal to the conditional probability of exceeding the total rainfall generating this event, under given conditions, characterized by the initial states and times of breakdown (both described by probability distribution functions).

Current research focuses on the comparison with the estimations of adjusted distributions for observed fluxes, and the behavior of the model at unobserved frequencies.

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