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Distributed hydrological modelling with lumped inputs

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Abstract This paper presents three different spatially distributed hydrological models and discusses the possibility of using them for flow simulation when only lumped information is available for the meteorological input. The three models, namely, AFFDEF, HYDROTEL and ModSpa, are applied on three French catchments from the MOPEX database. The purpose of the study is to provide examples to support the use of spatially-distributed approaches for real world applications even when fully distributed information is not available. The use of distributed models is advisable when at least a piece of distributed information is available such as a digital elevation model, a soil map or land-use data as for the three catchments and the models considered in this study. Overall, the applications presented here show that spatially distributed models can be successfully applied by using mixed lumped/distributed information. The performance of the models is comparable with the results that are usually obtained in real world applications of lumped models in similar situations.

Key words distributed models; lumped models; parameterization; ungauged catchments

INTRODUCTION

Rainfall–runoff hydrological models are largely used in applied hydrology for various applications such as river flow simulation, flood prediction, drought mitigation, catchment management, sediment and solute transport, and the design of hydraulic structures. Flow simulation on ungauged catchments is also a typical application of distributed models (Refsgaard, 1997). However, there are relatively few studies regarding this issue in the literature.

Hydrological models can be classified into two major types, lumped and distributed. Lumped models were developed since the 1960s (e.g. the Stanford catchment model, Crawford & Lindsey, 1966). They consider the catchment as an undivided entity and use lumped values of input variables and parameters. For the most part (for a review, see Singh, 1995), they have a conceptual structure based on the interaction between storage elements representing the different processes with mathematical functions to describe the fluxes between the storage (e.g. HSPF, Donigian *et al.*, 1995;

GR, Perrin *et al*., 2003). In the last two decades, lumped models were challenged by distributed models whose spatial structure allows the taking account of the spatial variability of processes within catchments and consequently the prediction of local hydrological responses for points within the catchment. Some distributed models are physically-based (e.g. SHE, Abbott *et al*., 1986) while others maintain a distributed description of catchment responses but in a much simpler way (e.g. TOPMODEL, Beven & Kirkby, 1978; HYDROTEL, Fortin *et al*., 2001). In distributed models, parameters need to be defined for every spatial element and for each process representing equation. In principle, parameter adjustment should not be necessary for this type of model because parameters should be related to the physical characteristics of the surface, soil and land use. However, in practical applications, calibration procedures are required for both lumped and distributed models; consequently the models require effective or equivalent values for some parameters.

Despite these difficulties, there has been a strong surge in the use of distributed modelling for applied hydrology over the last decade. However, in most practical applications, little geographical and spatial information is available.

This paper presents three spatially distributed models that can be applied to a wide range of real world applications and questions the use of distributed models for flow simulation taking into account the amount of information necessary to run them. We address this issue by applying the models (AFFDEF, Moretti & Montanari, 2006; HYDROTEL, Fortin *et al*., 2001; ModSpa, Moussa, 1991) on three catchments, both for gauged catchments on which the models can be calibrated, and for ungauged catchments for which no, or little, flow information is available. This paper is structured in three sections. The first presents the three catchments used in the applications, the second presents the structure and the parameters of the three models, and the third discusses the parameterization strategies and the results of the simulations.

THE STUDY SITES

Three catchments were used in the applications (Fig. 1): Le Guillec at Trézilidé located in Brittany, western France; Le Toulourenc at Malaucène, a tributary of the Rhone River, located in the Vaucluse; and Le Loup at Villeneuve Loubet located in the Alps Mountains in Alpes Maritimes, southern France. Hydrological data are presented in Chahinian *et al*. (The MOPEX 2004 database, this volume) and Table 1 shows the main characteristics of the three catchments. Catchment areas range between 45 and 279 km^2, and the outlet altitude ranges between 35 m (Le Guillec) and 2000 m (Le Loup). For all three catchments, the mean annual rainfall is of the same order and ranges between 1000 and 1200 mm, while the mean annual evapotranspiration varies between 700 and 1100 mm.

The three catchments have various hydrometeorological regimes. The Guillec catchment is located in western France, with an oceanic humid climate where baseflow is the major component of the hydrograph. The two other catchments have a Mediterranean climatic regime, characterized by a succession of drought and high intensity rainfall periods and by the high spatio-temporal variability of precipitation distribution

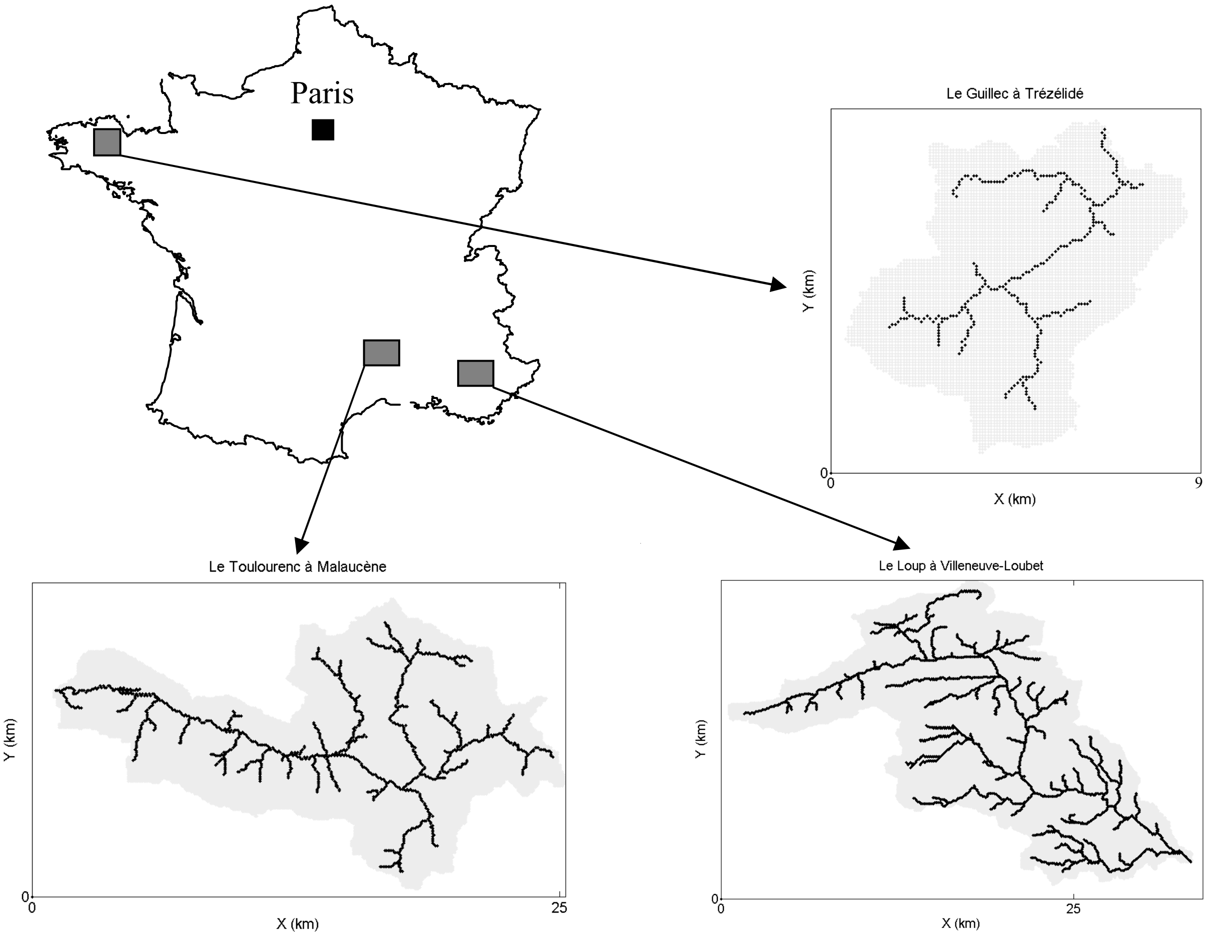

Fig. 1 Basin locations.

Table 1 Catchment characteristics.

Catchment	Area (km^2)	Outlet altitude (m NGF)	Mean annual rainfall 1995–2002 (mm $year^{-1}$)	Median of specific annual discharge ($m^3 s^{-1}$)	Mean annual evapotranspiration 1995–2002 (mm $year^{-1}$)
Le Guillec à Trézilidé (J3024010)	43	35	1015	0.67	686
Le Toulourenc à Malaucène (V6035010)	150	311	1059	1.32	1081
Le Loup à Villeneuve-Loubet (Y5615030)	279	2000	1159	4.47	1120

within and between years. The rainfall spatial variability is accentuated with altitude in the mountainous Loup catchment. During flood periods, overland flow is the main hydrological process, while during drought periods the main hydrological processes are evapotranspiration and baseflow. Note that while all models were used to simulate flows on all catchments in an ungauged mode (without calibration), HYDROTEL was only calibrated on the Guillec and Toulourenc catchments.

MODEL DESCRIPTIONS

This section presents the main structure, the hydrological processes, and the parameters of the three spatially distributed hydrological models (AFFDEF, HYDROTEL and ModSpa) used in the applications.

AFFDEF

AFFDEF is a spatially-distributed, continuous (in time) rainfall–runoff simulation model. The main characteristic of the model is that long simulation runs can be performed in limited computational times.

AFFDEF is raster-based. It takes as input the digital elevation model (DEM) of the catchment in raster form, as a rectangular matrix covering the catchment. The cells of the DEM can be of any size. It also needs as input rainfall and temperature data collected at an arbitrary number of raingauges and thermometers .

Many of the hydrological processes involved in the rainfall–runoff transformation have been schematized by using conceptual approaches. In particular, the model computes the local contribution at the surface runoff by applying a modified CN method (see Fig. 2(a)). In order to compute the soil storativity, one must provide the matrix of the CN numbers for any given DEM cell. The local contribution to the surface runoff and the groundwater flows are transferred to the catchment outlet by using a Muskingum-Cunge model with variable parameters, which are determined on the basis of the "matched diffusivity" concept (Orlandini & Rosso, 1996). The model has ten parameters (see Moretti & Montanari, 2006): the channel width/height ratio for the hillslope and channel network, the Strickler coefficients for the hillslope and the channel network, the critical source area, the saturated hydraulic conductivity, the width of the rectangular cross section of the subsurface water flow, the bottom discharge parameter for the infiltration reservoir capacity, the multiplying parameter for the infiltration reservoir capacity and the multiplying parameter for the interception reservoir capacity. Some of the model parameters have a well defined physical meaning and can be estimated on the basis of *in situ* surveys; the remaining parameters have to be optimized by calibration on the basis of some historical hydrometeorological records.

Although it can be used for any kind of catchment, it should be noted that AFFDEF simplifies the modelling of groundwater flows. Therefore it is best suited for basins where the runoff production is mainly due to infiltration excess.

The model may be freely downloaded at the web site http://www.costruzioni-idrauliche.ing.unibo.it/people/alberto, along with a user guide. A routine for performing automatic calibration that makes use of the SCE-UA genetic algorithm is included in the code.

HYDROTEL

HYDROTEL is a distributed hydrological model compatible with remote sensing and GIS (Fortin *et al.*, 2001). It is used operationally for flood forecasting in Québec

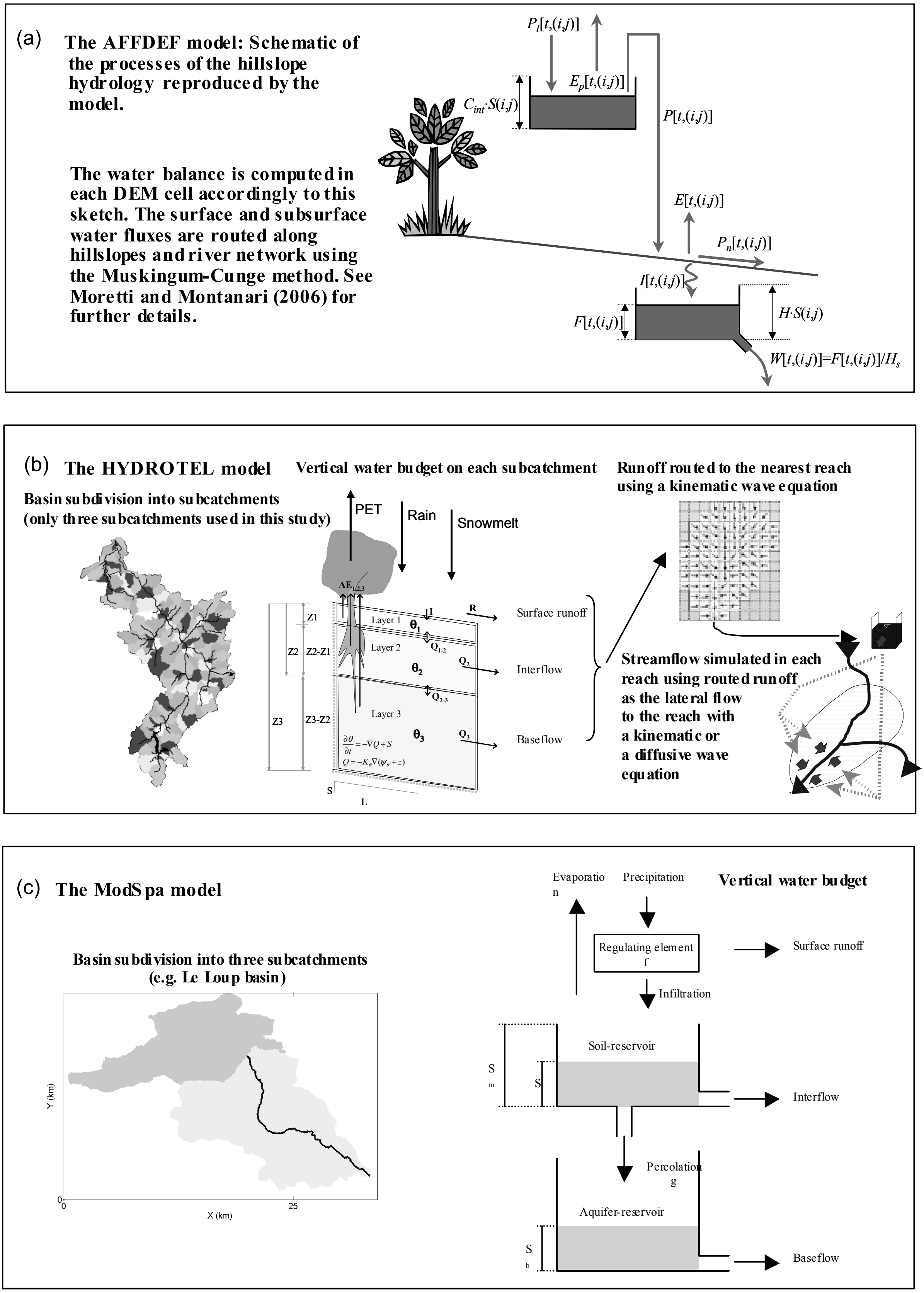

Fig. 2 The structure of the three spatially distributed mdodels AFFDEF (Moretti & Montanari, 2005), HYDROTEL (Fortin *et al.*, 2001) and ModSpa (Moussa, 1991).

(Turcotte *et al.*, 2004). Algorithms are derived as much as possible from physical processes, together with more conceptual or empirical algorithms. Natural units were chosen for the simulations: small subcatchments for the vertical water budget and flows towards the outlet of the unit, and river reaches for channel flow (Fig. 2(b)). Each subcatchment is characterized by a mean soil class and by the percentage of each land-use class (e.g. forest, agricultural zone, urban area, lakes, etc.).

The water budget procedure was developed so as to approximately represent the macro-processes related to infiltration and vertical redistribution of water in the "soil column" corresponding to the simulation unit. The soil column is divided into three layers (Fig. 2(b)). The surface layer is relatively shallow (5–20 cm), so as to represent the soil layer affected by evaporation over bare ground. While the first layer controls infiltration, the second layer can be associated with interflow and the third layer with baseflow. The Richards-1D equation is used to simulate flux exchange between the three layers. At each time step, the state variables calculated are the water content (θ_1, θ_2 and θ_3) of the three layers. HYDROTEL also simulates accumulation and melt of the snowpack using a mixed degree-day/energy-budget approach, and potential evapotranspiration using various methods such as Thornthwaite, Linacre, Penman-Monteith, Priestly-Taylor and the Hydro-Québec method. The kinematic wave model is used to simulate surface and subsurface flow on each subcatchment. Two simulation options are available for channel routing: the diffusive wave and the kinematic wave models. For this study, the Hydro-Québec method (Fortin, 1999) was used to compute potential evapotranspiration from daily minimum and maximum temperature, and the kinematic wave model was used for channel routing. Hence, the only meteorological inputs used in this study were temperature and precipitation. Note that the Hydro-Québec method for computing potential evapotranspiration includes a multiplicative parameter, c_{PET}, that is subject to estimation.

Over each subcatchment, the model parameters are the depth of each layer, the soil hydrodynamic properties of each soil layer (hydraulic conductivity at natural saturation, water content at natural saturation, residual water content, relationships between the hydraulic conductivity, the hydraulic head and the water content), the leaf area index, rooting depth of each land-use class and the geometric characteristics (area, slope, etc.). Each reach is characterized by the celerity of the flow. All of the hydrodynamic, land cover and geometric characteristics are estimated using a GIS and are typically not subject to estimation.

ModSpa

The main structure of the ModSpa (Modèle Spatialisé) spatially distributed hydrological was described by Moussa (1991). Digital elevation models are used to subdivide the catchment into right-banks, left-banks or source/head subcatchments and to extract the channel network. Over each subcatchment, the vertical water budget is computed using a two-layer model (Fig. 2(c)). The first layer, noted "soil reservoir", represents the upper soil layer where surface runoff, infiltration, interflow, percolation and evapotranspiration occurs. Infiltration is modelled using a reservoir Diskin-Nazimov model function of the precipitation, the total storage of the soil reservoir (S_m), the hydraulic conductivity at natural saturation of the soil (K_s), the maximum value of the hydraulic conductivity ($K_{max} = \alpha.K_s$ with α a parameter) and the soil humidity (S/S_m where S is the reservoir level). Evapotranspiration is calculated as a function of the above-listed parameters and the leaf area index (LAI) and the interflow is calculated as a function of the soil characteristics and the subcatchment surface slope. The second layer, noted “aquifer reservoir”, represents the aquifer from which the baseflow is calculated as a function of the level (S_b) of this reservoir and a constant k representing the recession curve of this reservoir. Three state variables are calculated as a function of time: the regulating function (f) which separates rainfall into surface runoff and infiltration, the level (S) in the soil-reservoir and the level (S_b) in the aquifer-reservoir. Then, a transfer function, based on the diffusive wave equation, is used to route flows on each subcatchment (surface runoff, interflow and baseflow) and then through the channel network. This equation depends on the celerity (C) and diffusivity on the subcatchments and on each reach. In the applications, we do not consider the spatial variability of the parameters and only six parameters were calibrated, five for the vertical water budget (LAI, Ks, S_m, α and k) and one for the transfer function (C).

MODEL APPLICATIONS

This section presents applications of HYDROTEL and ModSpa referring to both the ungauged mode, where the model parameters are estimated without using hydrometric measurements for optimization, and the gauged mode, where the hydrological model is calibrated by using a split-sample procedure. The model was calibrated by using the data observed in the 1 August 1995–31 July 1999 time period and validated by referring to the 1 August 1999–31 July 2002 period. The objective functions used are the Nash and Sutcliffe efficiency criteria, the bias and the Root Mean Square Error. The detailed equations are presented in Chahinian *et al*. “Compliation of the MOPEX 2004 results” (this volume).

AFFDEF was applied in a mixed gauged/ungauged mode. The application of AFFDEF was developed by following the same procedure described above for the gauged mode, but the calibration was performed using a limited data set. Only one flood event for each catchment was used for calibrating the model, by using a trial and error procedure (Table 2(a)). A limited calibration data set was used in order to test the model capability of providing a robust simulation even when a limited data set is available. Therefore, the modality of the AFFDEF application differs with respect to the other two models. The ungauged application of AFFDEF was not performed as no preliminary knowledge was available about the distribution of the AFFDEF parameters with reference to the hydrological behaviour of the three catchments. In fact, the previous applications of AFFDEF referred to catchments located in Italy and Germany. Therefore no information was available for French catchments or for catchments that can be considered similar to those considered here.

A priori parameter estimation (ungauged mode)

HYDROTEL is very sensitive to some parameters, but as most of them have a physical meaning, the *a priori* values of these parameters was based on expert experience in

Table 2 Comparison between the estimated parameters (ungauged mode) and the calibrated parameters (gauged mode) for the AFFDEF, HYDROTEL and ModSpa models.

(a) AFFDEF Model parameters	Ungauged mode	Gauged mode Guillec (J3024010)	 Toulourenc (V6035010)	 Loup (Y5615030)
Channel width/height ratio for the hillslope (-)	---	400	100	600
Strickler roughness for the hillslope ($m^{1/3}$ s^{-1})	---	0.5	2.0	0.1
Channel width/height ratio for the channel network (-)	---	20	20	30
Strickler roughness for the channel network ($m^{1/3}$ s^{-1})	---	15	25	8
Constant critical source area (km^2)	---	0.5	0.5	0.5
Saturated hydraulic conductivity (m s^{-1})	---	0.01	0.01	0.005
Width of the rectangular cross section of the sub-surface water flow (m)	---	0.5	0.5	0.5
Bottom discharge parameter for the infiltration reservoir capacity (s)	---	1000000	50000	79095
Multiplying parameter for the infiltration reservoir capacity (-)	---	1.10	1.00	0.20
Multiplying parameter for the interception reservoir capacity (-)	---	0.10	0.60	0.75

(b) HYDROTEL	Ungauged mode		Gauged mode	
Model parameters subject to calibration	Guillec (J3024010)	Toulourenc (V6035010)	Guillec (J3024010)	Toulourenc (V6035010)
c_{PET}	1.5	1.34	1.52	1.61
z_2	40 cm	37.5 cm	1.9 m	44.5 cm
z_3	80 cm	75 cm	2 m	89 cm

(c) ModSpa Model parameters	Ungauged mode	Gauged mode Guillec (J3024010)	 Toulourenc (V6035010)	 Loup (Y5615030)
K_s (× 10^{-7} m s^{-1})	7.00	0.69	5.56	4.40
S_m (m)	0.50	0.42	0.30	0.51
α	7.0	7.3	6.0	4.8
k (× 10^{-7} 1 s^{-1})	1.50	1.51	1.48	1.80
C (m s^{-1})	0.20	0.01	0.20	0.56
LAI	1.00	0.85	2.45	1.00

hydrological modelling in France using Rawls & Brakensiek (1989) pedotransfer functions. Also, since potential evapotranspiration was provided as an input in the meteorological database for the MOPEX experiment, the coefficient c_{PET} was set to a value such that the average potential evapotranspiration (PET) computed by HYDROTEL matched the average PET in the meteorological database. The parameters that were subjectively estimated by experts were the channel width, the vegetation rooting depth, and the depth of the third layer of soil (z_3), The depth of the bottom of the second layer (z_2) was set to half of z_3, and the depth of the first layer was kept at 5 cm.

ModSpa was applied by subdividing the catchment into three subcatchments: one source subcatchment, one right-bank subcatchment and one left-bank subcatchment as shown in Fig. 2(c). Parameters were considered constant on the three subcatchments and considered equal to those calibrated by Moussa (1991) on French catchments.

Table 2 shows the estimated parameters for HYDROTEL and ModSpa. The results show that the Nash and Sutcliffe efficiency of the two models ranges between 46% and 64% for the Toulourenc and the Loup catchments while negative values were obtained for Le Guillec catchment. The results can be considered satisfactory, especially if one considers that the hydrological observations available on these catchments were not used in any way to calibrate the models.

Parameter estimation through calibration (gauged mode)

AFFDEF was calibrated by following a trial and error procedure, as mentioned above. The values of the calibrated parameters are shown in Table 2(a) and Fig. 3 shows a comparison between measured and calculated discharge. HYDROTEL was calibrated by minimizing by trial and error the sum of the absolute relative bias on the daily flows and the absolute bias on the coefficient of variation of the daily flows (Fig. 4). Hence, individual streamflow observations were not used directly for model calibration: only the first two moments of daily flows (mean and variance) are used when computing the objective function. It is hoped that reasonable values for these two statistics can be estimated through statistical regionalization techniques, thus allowing one to use this calibration technique even for ungauged catchments. Manual calibration of HYDROTEL is quite tedious. Hence, only the parameters c_{PET}, z_2 and z_3 were calibrated, being amongst the most sensitive parameters in the model (Table 2(b)). An automated calibration algorithm is now available for HYDROTEL (see Turcotte *et al.*, 2003), but this technique was not available when the current study was performed. For this reason, manual calibration was only performed for the Guillec and Toulourenc catchments. The ModSpa calibration procedure was performed on six parameters Ks, Sm, α, k, C and LAI using a manual trial and error method minimizing the Nash and Sutcliffe criteria on the daily flows for the first five year period. Table 2(c) shows the calibrated parameters of ModSpa and Fig. 5 shows the simulation results.

Overall, the performances of AFFDEF, HYDROTEL and ModSpa are satisfactory when compared with similar applications presented in the literature for both lumped and distributed models: The Nash-Sutcliffe criteria ranges between 55% and 82% for the three models on the three catchments. Evaluation of the performances of AFFDEF should take into consideration the fact that this model was calibrated using a very limited data record.

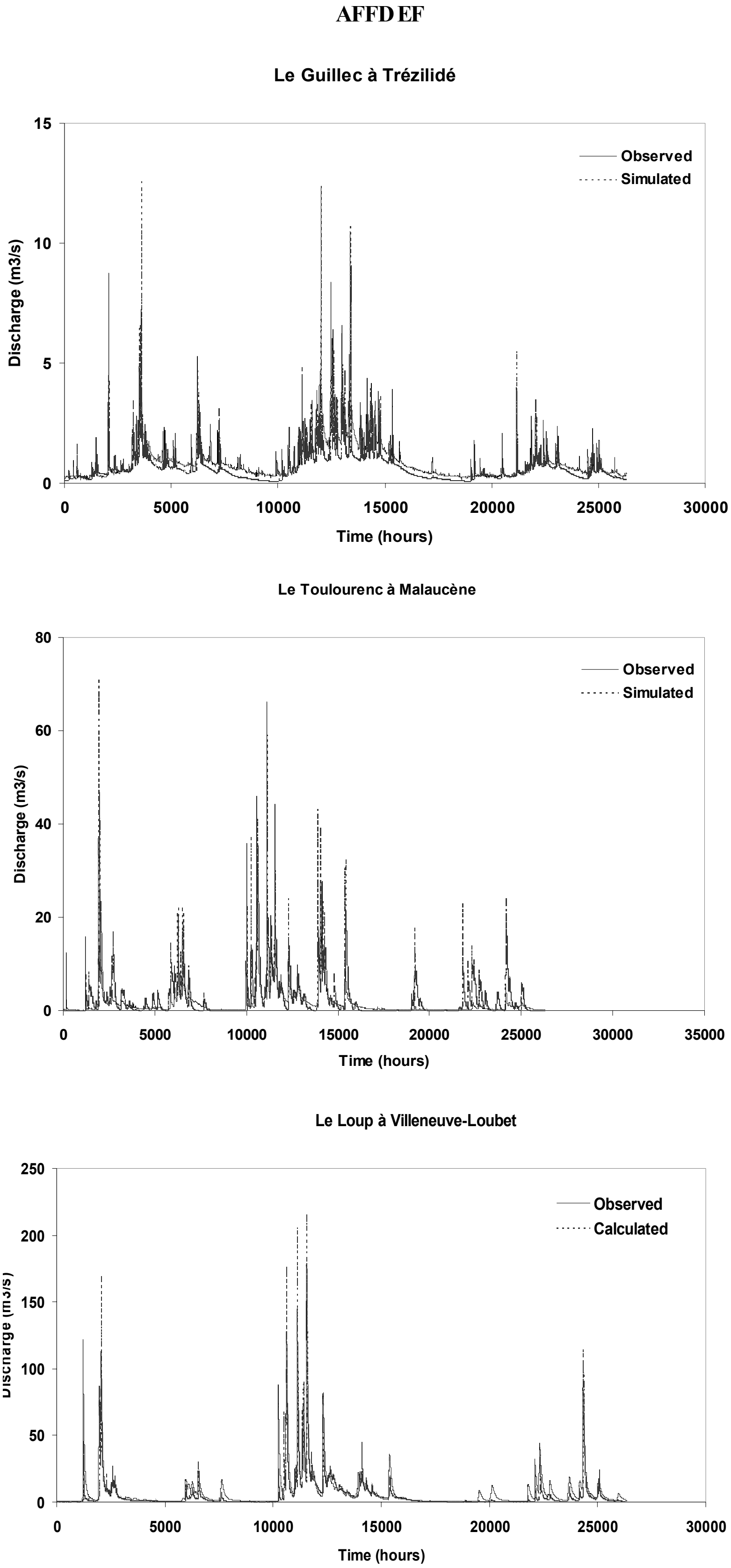

Fig. 3 Comparison between observed and calculated discharge for the AFFDEF model for the gauged mode.

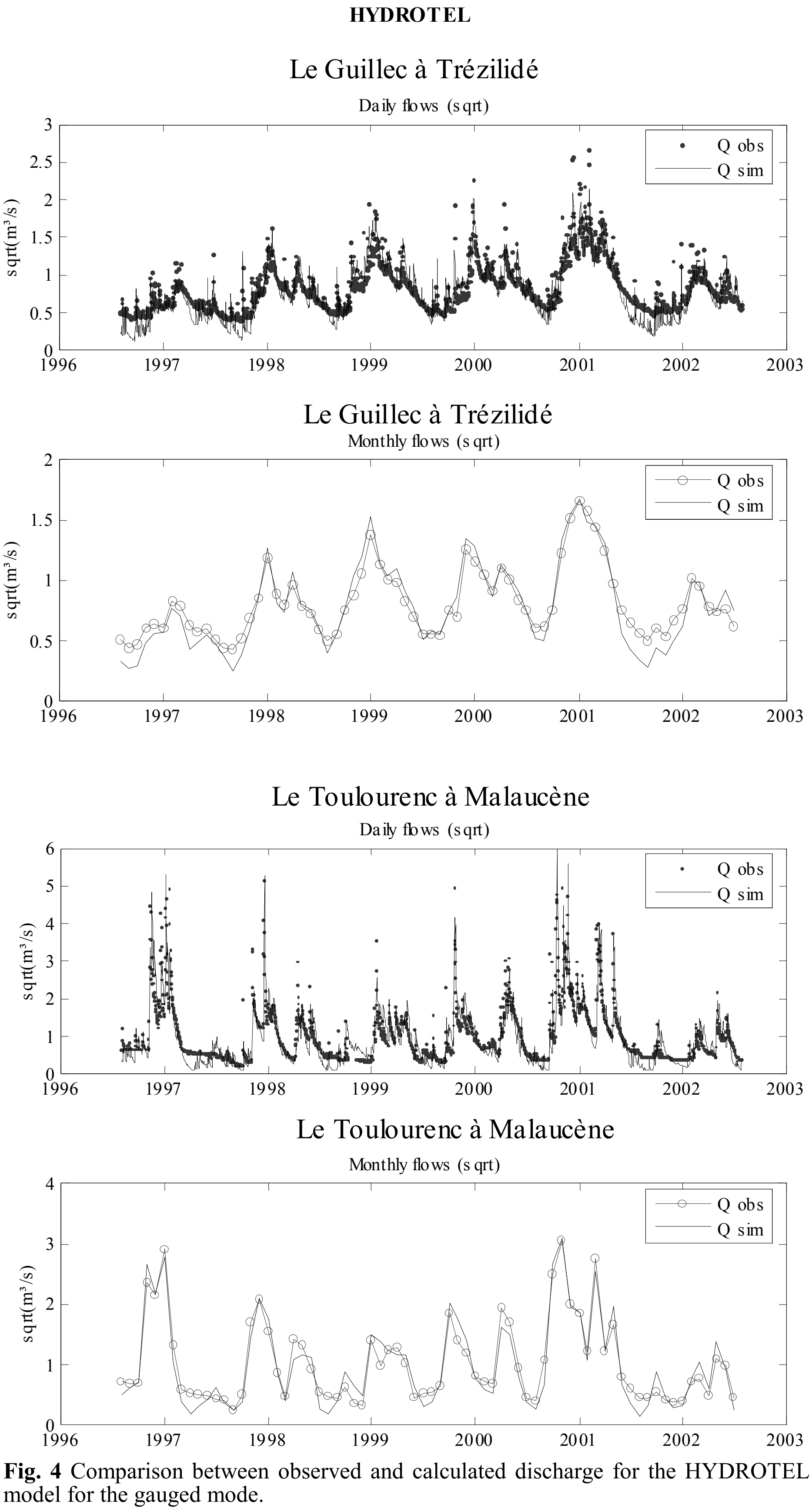

Fig. 4 Comparison between observed and calculated discharge for the HYDROTEL model for the gauged mode.

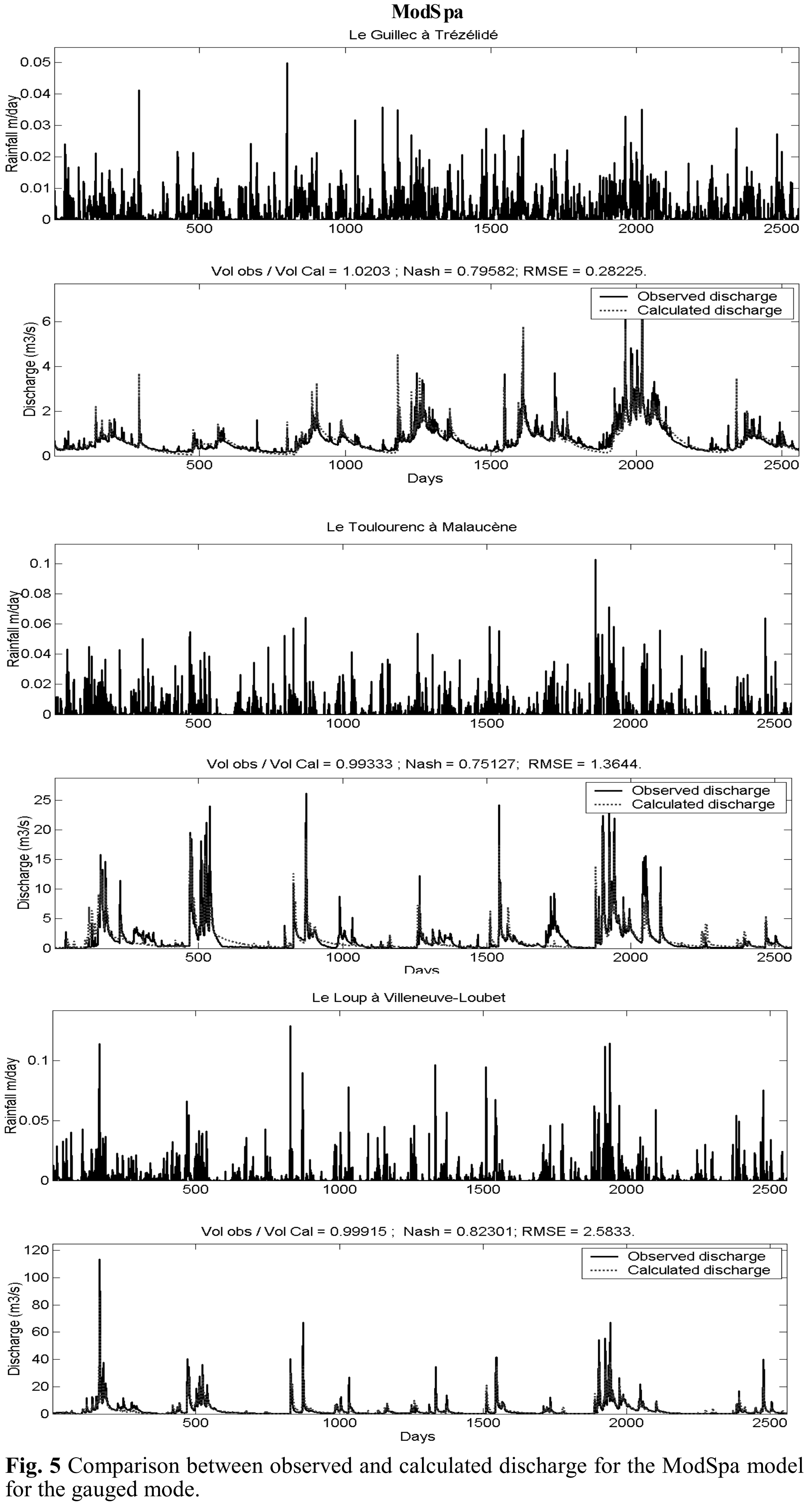

Fig. 5 Comparison between observed and calculated discharge for the ModSpa model for the gauged mode.

DISCUSSION AND CONCLUSIONS

The purpose of this study is to present and apply the three spatially distributed models described above by using only lumped values of input data such as precipitation and potential evapotranspiration. The aim is to discuss the usefulness of the application of these models for operational hydrology.

When only lumped information is available, or when applying hydrological models on ungauged catchments, the drawbacks in using a spatially distributed model are the impossibility of fully using the distributed information, the difficulty of obtaining values for distributed parameters, the model set-up time and the computation time. However, the reasons for using distributed models when the inputs are lumped are the possibility of downscaling some input variables such as precipitation and temperature as a function of the altitude available from the DEM (e.g. as in HYDROTEL) and the possibility of getting an insight to the hydrological response of the catchment from the DEM (e.g. as in ModSpa and AFFDEF). The use of spatially distributed models also allows one to identify and deal with data inconsistencies when flow measurements are available on internal subcatchments.

Overall, the applications presented here show that spatially distributed models can be successfully applied by using mixed lumped/distributed information. In fact, the performances obtained by the models are satisfactory and comparable with the results that are usually obtained in real world applications of lumped models in similar situations. The fact that HYDROTEL was calibrated only using the first two moments of daily flows, is also interesting, as this means that the data requirements for calibration are fairly low for this model. The same consideration applies to AFFDEF, which was calibrated using data observed during only one flood event and therefore equivalent to a nearly ungauged situation. The model produced satisfactory results for all catchments.

The results obtained in these applications confirm that the use of distributed models is advisable when at least a piece of distributed information is available. For instance, in the case considered here, a DEM was available for the three catchments and the models considered in this study benefited from the valuable information that the DEM itself can provide.

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