Multi-criteria assessment of the Representative Elementary Watershed approach on the Donga catchment (Benin) using a downward approach of model complexity

N. Varado, Isabelle Braud, S. Galle, M. Le Lay, L. Séguis, B. Kamagate, C. Depraetere

Hydrol. Earth Syst. Sci. Discuss., 2, 2349–2391, 2005
www.copernicus.org/EGU/hess/hessd/2/2349/
SRef-ID: 1812-2116/hessd/2005-2-2349
European Geosciences Union

Hydrology and Earth System Sciences Discussions

Papers published in *Hydrology and Earth System Sciences Discussions* are under open-access review for the journal *Hydrology and Earth System Sciences*

Multi-criteria assessment of the Representative Elementary Watershed approach on the Donga catchment (Benin) using a downward approach of model complexity

N. Varado[1,2], I. Braud[1,3], S. Galle[1,4], M. Le Lay[1], L. Séguis[4,5], B. Kamagate[5], and C. Depraetere[1]

[1]LTHE (UMR 5564 CNRS, INPG, IRD, UJF), BP 53, 38 041 Grenoble Cédex 09, France
[2]Cemagref UR Hydrosystèmes et Bio-Procédés, Parc de Tourvoie, BP 44, 92 163 Antony Cédex, France
[3]Cemagref UR Hydrologie-Hydraulique, 3 bis quai Chauveau, 69 336 Lyon Cédex 09, France

[4] IRD Benin, 08 BP 841, Cotonou, Benin
[5] Hydrosciences, Maison des Sciences de l'Eau, BP 64501 34 394 Montpellier Cedex 5, France

Received: 4 October 2005 – Accepted: 8 October 2005 – Published: 11 November 2005

Correspondence to: N. Varado (noemie.varado@cemagref.fr)

Abstract

This study is part of the AMMA – African Multidisciplinary Monsoon Analysis – project and aims at a better understanding and modelling of the Donga catchment (580 km^2, Benin) behaviour. For this purpose, we applied the REW concept proposed by Reggiani et al. (1998, 1999), which allows the description of the main local processes at the sub-watershed scale. Such distributed hydrological models, which represent hydrological processes at various scales, should be evaluated not only on the discharge at the outlet but also on each of the represented processes and in several points of the catchment. This kind of multi-criteria evaluation is of importance in order to assess the global behaviour of the models. We applied such multi-criteria strategy to the Donga catchment (586 km^2), in Benin. The work is supported by a strategy of observation, undertaken since 1998 consisting in a network of 20 rain gauges, an automatic meteorological station, 6 discharge stations and 18 wells.

The first goal of this study is to assess the model ability to reproduce the discharge at the outlet, the water table dynamics in several points of the catchment and the vadose zone dynamics at the sub-catchment scale. We tested two spatial discretisations of increasing resolution. To test the internal structure of the model, we looked at its ability to represent also the discharge at intermediary stations. After adjustment of soil parameters, the model is shown to accurately represent discharge down to a drainage area of 100 km^2, whereas poorer simulation is achieved on smaller catchments. We introduced the spatial variability of rainfall by distributing the daily rainfall over the REW and obtained a very low sensitivity of the model response to this variability. Our results suggest that processes in the unsaturated zone should first be improved, in order to better simulate soil water dynamics and represent perched water tables which were not included in this first modelling study.

HESSD

2, 2349–2391, 2005

1. Introduction

In order to face problems raised by the environmental policies and sustainable development, hydrologists are more and more asked to predict not only the discharge but also other hydrological variables such as water table depth, soil moisture, saturated surface fraction, or water fluxes in various points of the catchment. Numerous hydrological models had been developed to answer these questions and most of them are expected to become decision tools for watershed management.

Two kinds of modelling approaches are generally proposed and opposed: physically based models and conceptual models.

Physically based models rely on the use of plot scale equations. These equations ensure the mass, momentum and energy conservation but require a fine discretisation of the hydrological system. The SHE model (Abbott et al., 1986) is one of the most well-known. It has been improved by coupling a groundwater model to the original SHE model to lead to the MIKE-SHE model (Refsgaard and Storm, 1995). Many other distributed and physically based models are used such as the PMRS model (Leavesley and Stannard, 1995), the Soil and Water Assessment Tool (SWAT, Arnold and Fohrer, 2005), CATFLOW (Zehe et al., 2001), etc. Many discussions have occurred in the literature considering the pros and cons of this type of models (Beven, 1989, 1996; Refsgaard and Knudsen, 1996). First, the difficulty to collect physical properties (e.g. soil hydraulic conductivity, vegetation parameters) at the scale of the element grid is often underlined, as well as the poor knowledge of the boundary conditions of the system. The applicability of such models to large catchments is therefore difficult and raises the problem of equifinality in parameters estimation, especially when data for their internal validation are scarce (Grayson et al., 1992).

The alternative to physically based models is the use of conceptual models which structure is often based on several reservoirs linked to each other by (semi-)empirical laws. These models can be lumped, e.g. GR4J (Perrin et al., 2003), the SSARR model (Speers, 1995), the TANK model (Sugawara, 1995) but also partially distributed. They are generally valuable for operational water management such as flood forecasting or dam management. Parameters of such models are defined at the catchment scale by calibration but are not easily linked to measured physical properties. Therefore the predictive power of these models is questionable in case of climate or catchment changes and they cannot be easily applied on ungauged catchments.

According to Ambroise (1999), new developing strategies should aim at a combination between the trends of physical models and conceptual ones depending on the processes described, the objectives of the study and the state of knowledge of the catchment. Intermediate approaches should allow a derivation of hydrological variables inside the catchment, but keeping certain thrift in model parameters. This is the case of the REW concept, developed by Reggiani et al. (1998, 1999) as an intermediate approach combining the advantages of the usual model types. It rests on global balance laws for mass, momentum and energy formulated at the Representative Elementary Watershed (REW) scale. The strength of the approach is to translate the problem of model formulation into the derivation of exchange terms between the REWs and its zones (saturated, non-saturated, overland, concentrated and river flow), i.e. the closure relations. The research effort must therefore be concentrated on the formulation of correct parameterization of the corresponding hydrological fluxes, which can depend on scale. In this study, the closure system proposed by Reggiani and Rientjes (2005) is used.

The study presented in this paper was conducted on the Donga catchment (586 km^2) in Benin, West Africa, in the framework of the AMMA (African Monsoon Multidisciplinary Analysis) project. In this region, the impact of rainfall variability on water resources is a crucial question, the answer of which is central for the local population. When we started this work little was known on the major active processes of the catchment and especially on the amount of groundwater contribution to the streamflow. The REW approach was attractive in this context because it allows the determination of the fluxes between the various hydrological compartments in a distributed manner, with a minimum of data requirement.

The objectives of the study were threefold: i) to perform a first assessment of the REW approach to reproduce the catchment behaviour through the simulation and comparison of discharge, piezometric head and soil water content. If so, the model will help to test hypothesis of the catchment behaviour and particularly on the contribution of perched and deep water tables on the production of discharge; ii) illustrate the advantage of building a synergy between observation and modelling in order to progress in the use and validation of distributed hydrological models, and more specifically point out the deficiency in the measurement protocol; iii) use the multi-scale formulation of the REW model to get some answers to the following question: which spatial resolution, which complexity in modelled processes are required to which output? Intuitively, it is clear that the answer will be different is we only look at discharge at the monthlty time scale than if we look for a simulation of discharge, groundwater levels and soil moisture at the daily time scale.

To reach these goals, we performed a downward evaluation of the model by considering two spatial discretisations and an increasing complexity in the spatial variability of input variables and parameters. In order to assess the model structure, the evaluation of a distributed model representing various processes should be done on each hydrological compartment it represents and at various scales (Refsgaard, 1997; Michaud and Sorooshian, 1994; Bergström et al., 2002; Fortin et al., 2001; Anderton et al., 2002). A multi-criteria evaluation of the model was then performed in order to represent the discharge at the outlet, the groundwater dynamics and the saturation dynamics of soils at the season scale. Then, we looked at the representation of intermediary stations, in order to test the internal model structure. Eventually, the rainfall input was distributed at the catchment scale in order to see if the representation of discharge at every station could be improved by taking into account the spatial variability of rainfall.

2. Material

2.1. The Donga catchment and the AMMA project

The Donga catchment is part of the AMMA project (African Monsoon Multidisciplinary Analysis) that aims at a better understanding of the African Monsoon mechanisms and the interaction between the atmosphere and the continental surface (Lebel et al., 2003). The Upper Oueme watershed in Benin (Fig. 1) has been instrumented since 1997. A special effort has been done on the Donga catchment (586 km^2) in order to have a more detailed observation of processes governing the interaction between the soil and the atmosphere and to be able to close the water budget at a relatively small scale (Séguis et al., 2004). The measurement network, densified in 2002, is well suited for the evaluation of a distributed model representing various processes. In this numerical study with the REW model, we used data from 1998 to 2002. Table 1 summarises the data and the sensors used on the catchment.

The total annual precipitation on the Donga catchment is around 1200 mm that falls between April and October. Before 2002, 9 rain gauges were available on the catchment (Fig. 2). In 2002, 11 other rain gauges were installed in order to improve the description of the spatial variability of rainfall at the catchment scale.

An automatic meteorological station was installed on the catchment, in Djougou (see Fig. 2), in 2002. It provides meteorological data at a 15 minutes time step: air temperature, air humidity, wind speed, radiation and air pressure. A synoptic station is also available at a 130 km distance from the catchment, in the city of Parakou. These two stations allow the calculation of a Potential EvapoTranspiration (PET). The annual PET is about 1600 mm. A daily PET was used in the present study and was assumed constant for the whole catchment and calculated with the FAO method (FAO, 1998).

The soils are characteristic of the West African soils. The top horizon is a dry alteration of 1 or 2 m depth. Then, layers of alterites are found down to around 10–20 m depth, less and less altered with depth. The underlying bedrock is fractured with a crack density decreasing with depth. No quantitative data were available for the char-

HESSD
2, 2349–2391, 2005
Evaluation of the REW approach on the Donga catchment, Benin
N. Varado et al.

acterisation of alterites and the bedrock. Information from previous Sahelian studies (C. Leduc, personal communication) reports a huge decrease of porosity in the alterite horizons (3–5%), as compared to the soil surface. The surface layer as been sampled on a 3.5 km grid (66 sample points) in order to determine the soil hydraulic properties using simple infiltration tests (the Beerkan method, Braud et al., 2005). A pedologic map of the region is also available.

Since 1998, the discharge data are available at the outlet. In 2002, 5 others stations were installed in order to monitor 5 nested watersheds and 2 small upstream watersheds (Fig. 3). The annual runoff at the outlet varies from 149 mm in 2002 to 413 mm in 1998, with, respectively, a runoff coefficient from 15% to 30%. In terms of precipitation and discharge, the years 1998 and 1999 are rather humid and 2000, 2001 and 2002 are rather dry, compared to historical data of the Upper Oueme river, from 1925 to 1984 (Le Barbé et al., 1993). Table 2 summarises the rainfall and runoff characteristics for the period 1998–2002.

The discharge is not permanent within the year, in any point of the catchment. The discharge at the outlet begins by the end of June, and shows a delay of about 90 days respect to the beginning of rainfall. It stops by the end of October. The 3 months delay shows that the runoff at the catchment scale cannot only come from direct surface runoff but that water should be stocked within the soils in various aquifers and released later. It raises questions of the partition between surface runoff and infiltration and the contribution of groundwater or soil water stock to the streamflow.

In 2002, 18 well levels were followed by automatic thalymedes (OTT) or readers (Fig. 2). All these wells are used as domestic wells by the village population. No quantification of the water extracted is available up to now. Some of these 18 wells are unusable during the dry season because their level is too influenced by the pumping and they become dry. The data were used assuming that the highest measure of the day (in the morning, before the first pumping) represents the equilibrium level of the water table.

All these wells are situated within the alterite horizons and are usually higher than the neighbouring river reach. No measure from a deeper groundwater table was available at the time of our study. However, some piezometers were installed in 2003 in order to follow the deeper aquifer and will provide additional information on the generation of streamflow.

From 2003, two local stations of soil moisture measurement were installed in order to close the water budget at small scale: one is in a forest and another is on a fallow field. These two stations measures soil water content, soil matrix potential, and soil temperature on the first meter of soil. Data from the fallow field were used in order to evaluate qualitatively the variation of soil saturation within the year, simulated by the REW model. These measures do not represent the whole profile but according to recent geochemical results, the saturation of the first meter of soil plays an important role in the production of discharge.

As shown in this section, the instrumentation of the Donga catchment is particularly well designed to assess the performance of a distributed hydrological model on the representation of various hydrological processes and their importance at the catchment scale. In this study, we focus on the discharge at various stations, the groundwater dynamics and the soil moisture dynamics throughout the season, which consist in the simulation objectives

2.2. The REW-v4.0 model

The model used relies on the REW concept developed by Reggiani et al. (1998, 1999) and recently illustrated on two catchments by Reggiani and Rientjes (2005), Fenicia et al. (2005) and Zhang et al. (2005). These three recent articles describe well the version of the model used in this study; only a brief summary is presented here. The catchment is divided into several Representative Elementary Watersheds (REW) using the TarDEM software (Tarboton, 1997). The number of REWs is controlled by the Strahler order used as threshold. The REWs are partitioned into 5 different zones which are: the river reach (R Zone), the unsaturated zone (U Zone), the saturated zone (S Zone), the concentrated flow zone (C Zone), and the saturated overland flow

HESSD

2, 2349–2391, 2005

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄| |►
◄ ►
Back | Close
Full Screen / Esc
Print Version
Interactive Discussion

EGU

zone (O Zone). For each of these zones, an averaging procedure allows the derivation of the mass and momentum balance equations at the REW scale.

Each zone exchanges fluxes with the 4 other zones of the same REW. Figure 4 shows the model structure and the interaction, in terms of water fluxes, between the various zones (i.e. the processes represented). The river reaches are linked upstream and downstream. The saturated zone can also exchange fluxes with all their neighbouring REW's S Zone.

For each zone, the mass and momentum conservation equations are written at the centre of gravity of the zone. These equations are shown to have a common and simple form as they are ordinary differential equations (ODE) (Reggiani et al., 1998).

$$\frac{d\psi}{dt} = \sum_i e_i^{\psi} + R + G \tag{1}$$

where Ψ is the conservative quantity (mass or momentum), e_i^{ψ} is an exchange of mass or momentum between the various zones or between the same zone of two neighbouring REWs. R is an exterior supply and G an intern production. The resolution of the ODE by a Runge-Kutta algorithm, allows the determination of a characteristic and the mean velocity within each zone (Table 3).

The e_i^{ψ} terms of the ODE are the unknowns of the problem. A closure of the system within a single and physically consistent procedure was proposed by Reggiani et al. (1999) and Reggiani and Rientjes (2005). This procedure has led to a linearized parameterisation of the fluxes.

We emphasize, here, the fact that, in the REW model, the subsurface is conceptualised as two underlying reservoirs. The unsaturated zone is an homogeneous reservoir characterised by mean soil properties. It is situated above a saturated zone, lying on the bottom of the system. The boundary between both, which is the average saturated zone height is calculated at each time step and can move upwards and downwards.

3. Method

A Digital Elevation Model with a 30-m resolution was available for the Donga catchment discretisation. Two discretisations were used in order to see if one is more accurate for the representation of one or several simulation objective. 2nd and 3rd orders lead respectively to 117 and 23 REWs (Fig. 5).

Table 4 lists the various inputs, conditions and parameters needed, at the REW scale, to run the model. The runs started on the 1 January, as initial conditions in terms of discharge and surface runoff are known (null in any point of the catchment). In order not to be influenced by the initial degree of saturation in the unsaturated zone and the initial position of the water table, the simulations were run three times, injecting final conditions as initial ones when restarting the simulation. Only the third run was used in the analysis of the results.

The soil parameters were taken, first, as the mean of the Beerkan campaign values. A try of spatialisation of soil properties from the combination of the infiltration measures and the pedologic map (Varado, 2004) was not successful and is not presented here. Hydraulic coefficients for river links and surface were chosen from tables available in the literature (Chow et al., 1988).

As no information was available for the aquifer boundary conditions, every boundary was supposed to be permeable but no flux was imposed at the boundary. The possible flux is calculated directly by the Hardy-Cross algorithm (cf. Reggiani and Rientjes, 2005). The mean depth of the bedrock was chosen at a fixed position under the river reach (0 to 8 m).

In a top-down evaluation of the model ability to reproduce discharge groundwater level and soil saturation, a first simulation was run with homogeneous input and homogeneous properties for the whole catchment. In view of the first results, soil parameters were adjusted to improve the model representation of discharge. Then, the rainfall input was distributed between the REWs, in order to see if it allowed a better description of the discharge in several points of the catchment.

The simulations were evaluated on discharge with the efficiency from Nash and Sutcliffe (1970) at the daily, decadal and yearly time scales:

$$E = 1 - \frac{\sum_{i=1}^{n_{obs}} (Y_{imod} - Y_{iobs})^2}{\sum_{i=1}^{n_{obs}} \left(Y_{imod} - \overline{Y_{obs}}\right)^2} \quad (2)$$

where Y_{imod} is the simulated variable, Y_{iobs} is the observed variable, $\overline{Y_{obs}}$ is the mean of the observations and n_{obs} is the number of observations. In order to reduce the weight of large discharge values and to better take into account the dry season, the efficiencies were calculated on the square root values.

A qualitative evaluation of the groundwater levels and the soil saturation was also performed.

4. Results and discussion

4.1. First application of the REW model using soil surface parameters

The first simulation was performed with the soil parameters from the surface measurements campaign, i.e. without any calibration. The soils parameters (θ_s, K_s, λ) were the same on every REW and equal to the mean of the measured values from the Beerkan infiltration field campaign. θ_s, K_s were the same for the Unsaturated zone and the Saturated zone.

Figure 6 shows the decadal discharge at the outlet for the year 1999 and 2000, with a 3rd Strahler order discretisation. Even if the annual volume is quite accurately represented (Fig. 7), two major problems appear. First, the delay of 3 months between the beginning of the rainfall and the discharge was not reproduced by the model: the model produced discharge as soon as rainfall started. Secondly, in the height of the rainy season (August, September, and October) the model underestimated the discharge at the outlet. Efficiency on daily discharge was equal to 0.35 and 0.40 on decadal discharge. Even if these efficiencies are of the same order of magnitude as the figures presented by Reggiani and Rientjes (2005), the Donga catchment behaviour seems not to be captured by the model. Looking at the saturated and unsaturated zones, the analysis is the same. For these two zones, the modelled yearly dynamics (of the degree of saturation and the water level, respectively), were very flat. In the REW-v4.0 model, the rainfall produced direct runoff instead of wetting the soils in the first part of the season. The soils remained dry and the zone S level remained quite the same, throughout the season.

So the bad temporal distribution of the discharge within the season seemed to be linked to a lack of soil infiltration, probably due to a problem of soil parameters estimation.

4.2. Calibration

Remember that the infiltration measurements were done only for the surface horizon. But we noticed a great variation of soil properties (and infiltration capacity) when installing the local soil moisture station, especially between 20 cm and 40 cm depth. As the Unsaturated zone requires homogeneous parameters, we chose to find an equivalent parameter set by calibration. The adjustment of θ_s and K_s was conducted with the aim to better represent the discharge at the outlet, especially the 3 months delay in runoff and the peak flow in the height of the rainy season. The calibration was performed manually at the 3rd and 2nd Strahler order, with θ_s and K_s still homogeneous at the catchment scale and identical in the Saturated zone and the Unsaturated zone. We selected 1999 and 2000 as a calibration period, as these two years are, respectively, rather dry and rather humid. The calibrated values of K_s were found not to be identical between order 2 and order 3 (respectively 1.10^{-5} m.s^{-1} and 5.10^{-6} m.s^{-1}), suggesting a scale definition of K_s. On the contrary, θ_s was found to be identical but very low: 0.03 m^3.m^{-3} (i.e. only 10% of the surface value). This is consistent with a huge decrease of porosity with depth and a preponderance of the alterite horizon with respect to the surface one.

Figure 8 shows the decadal volume at the outlet, for the calibration period. The simulated discharges at the beginning of the season (April, May and June) did not perfectly match the observed ones but were largely reduced by the calibration. Peaks simulation in the height of the season, was also very much improved. The global efficiency reached 0.63 with a 2nd order discretisation and only 0.53 with a 3rd order discretisation. The total runoff volume was slightly deteriorated by the calibration. At the daily time step, the efficiency was also improved with a value of 0.55 and 0.57, respectively, with a 2nd and 3rd order discretisation.

The validation period was taken as the whole 1998–2002 period. So, the year 1998, 2001 and 2002 are independent from the calibration period. Table 5 shows for each year the efficiencies calculated on the daily, decadal and monthly discharge. The efficiencies were globally as good on the validation period (1998, 2001 and 2002) as on the calibration period (1999, 2000). The simulation of the year 2002 was less accurate than for the other year, probably because 2002 was the driest year. Looking at the same time step, the efficiencies were greater with a 2nd order discretisation than with a 3rd order one. This suggests that a 2nd order discretisation is more appropriate than a 3rd one for the simulation of the discharge at the outlet.

4.3. Effects of the calibration on the internal state variables

The calibration was performed in order to improve the simulation of discharge at the outlet but also with the aim of increasing infiltration in the unsaturated zone and then in the saturated zone.

4.3.1. Soil water content

The top graph of Fig. 9 shows an example of soil water content changes for the years 1999 and 2000 before the calibration and after the calibration of the soil parameters.

Whereas using the surface parameter this degree of saturation never exceeded 0.8 and never decreased below 0.6, the use of calibrated parameter allowed an almost saturated state at the end of the rainy period (during several weeks in September or October) and a drastic decreases by the dry period (March and April). The bottom graph of Fig. 9 shows the saturation degree measured on the fallow field in 2004 (we remind that these data were not available for the simulation years). As the first meters of soil are probably the most contributive to the streamflow, these measures gave an overview of the variation of the degree of saturation within a year, at which the simulation should aim. The comparison of the two graphs showed that the use of the calibrated parameters led to a consistent simulation of soil saturation. This first comparison of soil saturation should be completed as soon as other data are available: following years and others stations on various land use.

4.3.2. Groundwater level

The comparison between observed and computed groundwater levels was quite uneasy. Whereas observations are discrete in space, the model provides a water table level averaged at the REW scale. Comparison with a single well is not very relevant; but a comparison with various wells situated on a same REW may provide a range of dynamics at the REW scale. At the 3rd Strahler order, 3 wells are located in the REW no. 1: Ananinga, Foyo and Gaounga, which can provide a range of behaviour for this REW. Figure 10 shows the groundwater level calculated for the REW no. 1 and the three observed wells for the year 2000, 2001 and 2002. The annual amplitude of the groundwater level was well reproduced by the model (8 to 10 m). A 4 months delay was simulated between the rainfall input and the level rise, i.e. an overestimation of the delay of about 1 month. The major problem in this simulation was the absolute elevation of the water table; as the modelled water table was about 30 to 50 m deeper than the measured water table. If we compared the levels in relative elevation with respect to the soil surface (not shown), it led to the same conclusions: whereas the modelled water table was between 12 and 20 m depth, the observed water table reached the soil surface at the end of the rainy season and is between 10 and 15 m during the dry season.

The wells are bored in the alterite horizon. New geophysical studies reveal that these water tables may be perched water tables, disconnected, not lying on the bedrock and higher than the river bed (Wubda, 2003). Geochemical measurements (Kamagaté et al., 2004) also suggest a major contribution of these perched water tables to the runoff production, at least at the beginning of the season. Another deeper water table exists but no qualitative data is available at this time of the study.

In the REW model, the S Zone is a conceptual reservoir for the groundwater stock, which might include both perched and deep water tables. Thus, the simulated groundwater level is a combination of these two entities and might better be seen as the water stock of all the saturated zones. Within the model, no distinction between these two hydrological compartments can be made as the unsaturated zone is also a conceptual and homogeneous reservoir. If we want to explicitly represent these perched water tables, we have to modify the U Zone representation, and be able to take into account heterogeneous soils. The corresponding module has been built, based on a efficient and accurate solution of the Richards equation (Ross, 2003; Varado et al., 2005a) where a sink term for root extraction has been added (Varado et al., 2005b) but has not been used in this first study.

4.3.3. Other fluxes

The comparison of the exchange fluxes between the various zones of the model showed a major exchange between the saturated surface (zone O) and the river (zone R) compared to all other fluxes. This can be seen as a model compensation for the weakness in the unsaturated zone conceptualisation. Such a model behaviour coupled with the modelled annual amplitude of groundwater can be seen as an acceptable agreement between the modelled system and the catchment behaviour.

The validation of the Donga modelling with three objectives (discharge at the outlet, groundwater dynamics, and moisture content dynamics) allow us to gain some confidence in the system representation. The simulated behaviour throughout the year was rather consistent with the knowledge of the Donga catchment we had at the study time.

4.4. Representation of intermediate stations

In 2002, 5 more gauging stations were installed. These new stations allowed us to test the model ability to reproduce intermediate discharge stations which were not used in the calibration process; and under this goal to test the model internal structure.

Table 6 shows the efficiency on squared daily discharge for every station and each discretisation and Fig. 11 shows the simulated and observed discharge at every station for the 3rd order discretisation. It shows that, globally, the discharge at intermediary stations was accurately simulated and that for some stations the efficiency is even greater than at the outlet: Route de Kolokondé, Koua and Nékété stations at the 3rd order, and only Nékété station at the 2nd order.

The two head catchments, Ara and Bokpérou, were poorly simulated with both discretisations. The 0.45 value of the efficiency, for the Ara catchment, is misleading because the simulated discharge was too erratic and did not really match the observed discharge. For both stations, there was a problem of spatial discretisation and temporal scale. A finer discretisation (1st order) may help to better reproduce the processes on these catchments. Furthermore, the response time of these upstream catchments is smaller than the daily time scale used in this study. The model, which used daily rainfall input, was unable to catch the rapid dynamics but would probably be able to when using hourly or event data.

To sum up, the model was able to accurately simulate the discharge at intermediary stations as soon as the drainage area was above 100 km^2. Below this size, the spatial and temporal discretisation and/or the physical mechanisms were not complex enough to well reproduce the discharge, especially on small upstream catchments.

4.5. Spatial distribution of rainfall

Up to now, the rainfall input was homogeneous at the catchment scale: each REW received the same mean daily rainfall, obtained by block kriging over the whole catchment. The 2002 raingauges network allowed a finer description of rainfall by determining a mean daily precipitation with kriging at the REW scale. At the 2nd order, the total annual precipitation on the REWs ranged from 923 mm to 1191 mm.

For the two discretisations and the year 2002, Table 7 gives the efficiencies at the outlet when considering homogeneous or distributed rainfall. The rainfall distribution slightly improved the efficiencies (for both orders and at every time step), but at most by 3 points.

Figure 12 shows the decadal volumes simulated at the outlet (with a 2nd order discretisation) for the year 2002 when the rainfall is homogeneous or distributed, compared to the observed volumes. The slight improvement seen on the efficiency came from the peak simulation in the height of the season, even if it is still underestimated. The remaining overestimation of the volumes at the beginning of the season is not reduced by the rainfall distribution.

Table 8 shows the daily efficiency at every station in 2002. The spatial distribution of rainfall had not a greater influence on discharge at intermediary stations than on discharge at the outlet. The efficiencies were improved by 3 points at most, and some simulations had similar efficiency or were deteriorated by 1 to 3 points. The simulations of the small upstream catchments were not particularly improved.

5. Discussion and conclusion

The aim of this first application of the REW concept to the Donga catchment was to test its ability to reproduce the discharge at various points of the catchment, the groundwater dynamics and the variation in soil water content across the season. To correctly represent the three months delay between the beginning of the precipitation and the beginning of runoff at the outlet, the soil parameters of the model had to be calibrated. The need of calibration can be seen as a lack of information concerning the alterite horizon. Nevertheless, this is also linked to the impossibility to represent explicitly the perched water tables with such a conceptualisation of the subsurface, in the REW model: two homogeneous reservoirs, one saturated, the other unsaturated. The necessity to adjust soil parameters to take into account the vertical heterogeneity of the soils pleads for a more realistic simulation of the non-saturated zone dynamics. The geophysical survey (Wubda, 2003) provides a new description of the soil profile that should be incorporated into the model, at medium term. In parallel, the evaluation of the simulated groundwater level has to be faced incorporating a distinction between deep groundwater aquifer and perched water tables. These perched water tables seem to play an important role in the discharge production, according to the geochemical measurements (Kamagaté et al., 2004). The inclusion of a more complex vadose zone module (Varado et al., 2005b) into the REW model is then expected to improve not only the simulation of the water table level in the alterite horizon and the soil moisture variations but also the simulation of the discharge at the various stations.

For catchments with a surface larger than 100 km^2, the model allowed an as accurate simulation of discharges at intermediary stations as at the outlet. For smaller sub-catchments, the simulated discharge was too erratic. This result suggests that a more physical conceptualisation, a finer spatial discretisation and finer temporal inputs must be incorporated into the model to better represent the usptream catchment.

The poor improvement of discharge simulation due to the inclusion of the spatial variability of rainfall suggests that the spatial variability of inputs is a second order problem, at least for the rainfall, in our simulation, as compared to the fair representation of soil profiles.

This first hydrological modelling of the Donga catchment showed the interest of a multi-scale and multi-variables instrumentation of the catchment. We also found that model simulations could help in defining a better strategy to monitor the catchment. A strong effort has still to be put on the monitoring/estimation of the evapotranspiration component and its evaluation at the catchment scale. In this direction, the planned used of scintillometers could provide estimation at the small catchment of evapotranspiration fluxes, which could be compared with the estimation provided by the model.

Finally, we would like to underline the interest of the REW model formulation: it is rather easy to refine the spatial resolution by considering smaller order river reaches. Furthermore, as the challenge lies in the determination of exchanges fluxes, various levels of complexity for the determination of these fluxes can be tested without modifying the model structure. We will explore this possibility in a next step of the hydrological modelling of this catchment.

Acknowledgements. The authors thank all the scientists that helped in collecting the soil hydraulic properties with the Beerkan method: R. Angulo-Jamarillo, S. Boubkraoui, J.-M. Bouchez, D. De Condappa, G. Derive, A. G. Gossou, R. Haverkamp, P. Reggiani, J. S. Ugalde, and A. Afouda. P. Reggiani is also thanked for providing the version of the REW-v4.0 model used in the study and for his assistance in its use. The work was partly funded by the French National Program /ACI Ecosphère Continentale, PNRH axis.

References

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., and Rasmussen, K.: An introduction to the European Hydrological System – Système Hydrologique Européen, "SHE", 1: History and philosophy of a physically-based distributed modelling system, J. Hydrol., 87(1/2), 45–59, 1986.

Ambroise, B.: La dynamique de l'eau dans le bassin versant – Processus, Facteurs, Modèles, Edition HGA, Bucarest, 200 pp., 1999.

Anderton, S., Latron, J., White, S. M., Llorens, P., Gallart, F., Salvany, C., and O'Connell, P. E.: Internal evaluation of a physically-based distributed model using data from a Mediterranean mountain catchment, Hydrol. Earth Syst. Sci., 6, 1, 67–83, 2002, SRef-ID: 1607-7938/hess/2002-6-67.

Arnold, J. G. and Fohrer, N.: SWAT2000: current capabilities and research opportunities in applied watershed modelling, Hydrol. Process., 19(3), 563–572, 2005.

Bergström, S., Lindström, G., and Pettersson, A.: Multi-variate parameter estimation to increase confidence in hydrological modelling, Hydrol. Process., 16, 413–421, 2002.
Beven, K. J.: Changing ideas in hydrology – the case of physically based models, J. Hydrol., 105, 157–172, 1989.
Beven, K. J.: A discussion of distributed hydrological modelling, in: Distributed Hydrological Modelling, edited by: Abbott, M. B. and Refsgaard J. C., Kluwer Academic, pp. 255–278, 1996.
Braud, I., De Condappa, D., Soria, J. M., Haverkamp, R., Angulo-Jaramillo, R., Galle, S., and Vauclin, M.: Use of scaled forms of the infiltration equation for the estimation of unsaturated soil hydraulic properties (Beerkan method), European J. Soil Sci., 56(3), 361–374, 2005.
Chow, V. T., Maidment, D. R., and Mays, L. W.: Applied hydrology. Civil Engineering Series, McGraw-Hill International Edition, 1988.
FAO: Crop Evaporation – Guidelines for computing crop water requirements, Irrigation and Drainage paper, 56, Rome, 1998.
Fenicia, F., Zhang, G. P., Rientjes, T., Hoffmann, L., Pfister, L., and Savenije, H. H. G.: Numerical simulations of runoff generation with surface water-groundwater interactions in the Alzette river alluvial plain (Luxembourg), Phys. Chem. Earth, 30(4–5 SPEC. ISS.), 277–284, 2005.
Fortin, J.-P., Turcotte, R., Massicotte, S., Moussa, R., Fitzback, J., and Villeneuve, J.-P.: Distributed watershed model compatible with remote sensing and GIS data. 2. Application to Chaudière watershed, J. Hydrol. eng., 6(2), 100–108, 2001.
Grayson, R. B., Moore, I. D., and McMahon, T. A.: Physically based hydrologic modeling. 2 – Is the concept realistic?, Water Resour. Res., 28(10), 2659–2666, 1992.
Kamagate, B., Favreau, G., Séguis, L., Seidel, J.-L., and Le Barbé, L.: Flux nappe-rivière en milieu tropical de socle au Bénin (haut Ouémé), 20è colloque de Géologie Africaine, 2–7 June 2004, Orléans, France, 2004.
Le Barbé, L., Alé, G., Millet, B., Texier, H., Borel, Y., and Gualde, R.: Les Ressources en eaux superficielles de la République du Bénin. IRD, Collection Monographies Hydrologiques, no. 11, Paris, 469 pp., 1993.
Leavesley, G. H. and Stannard, L. G.: The Precipitation-Runoff Modeling System-PRMS, in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resour. Publications, Highlands Ranch, Colorado, pp. 281–310, 1995.
Lebel, T., Redelsperger, J.-L., and Thorncroft, C.: African Monsoon Multidisciplinary (AMMA):

An international research project and field campaign, Exchanges, 27(8), 52–54, 2003.
Michaud, J. and Sorooshian, S.: Comparison of simple versus complex distributed runoff models on a midsized semiarid watershed, Water Resour. Res., 30(3), 593–605, 1994.
Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models: 1. A discussion of principles, J. Hydrol., 10, 282–290, 1970.
Perrin, C., Michel, C., and Andreassian, V.: Improvement of a parsimonious model for streamflow simulation, J. Hydrol., 279(1–4), 275–289, 2003.
Refsgaard, J. C.: Parametrisation, calibration and validation of distributed hydrological models, J. Hydrol., 198, 69–97, 1997.
Refsgaard, J. C. and Knudsen, J.: Operational validation and intercomparison of different types of hydrological models, Water Resour. Res., 32(7), 2189–2202, 1996.
Refsgaard, J. C. and Storm, B.: MIKE SHE, in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resour. Publications, Highlands Ranch, Colorado, pp. 809–846, 1995.
Reggiani, P., Sivapalan, M., and Hassanizadeh, S. M.: A unifying framework for watershed thermodynamics: balance equations for mass, momentum, energy and entropy, and the second law of thermodynamics, Adv. Water Resour., 22(4), 367–398, 1998.
Reggiani, P., Hassanizadeh, S. M., Sivapalan, M., and Gray, W. G.: A unifying framework for watershed thermodynamics: Constitutive relationships, Adv. Water Resour., 23, 15–39, 1999.
Reggiani, P. and Rientjes, T. H. M.: Flux parameterization in the representative elementary watershed approach: application to a natural basin, Water Resour. Res., 41, W04013, doi:10.1029/2004WR003693, 2005.
Ross, P. J.: Modeling soil water and solute transport – Fast, simplified numerical solutions, Agronomy Journal, 95, 1352–1361, 2003.
Séguis, L., Galle, S., Arjounin, M., Boubkraoui, S., Bouchez, J.-M., Braud, I., Cazenave, F., Depraetere, C., Gosset, M., Laurent, J.-P., Le Barbé, L., Malinur, F., Cappelaere, B., Favreau, G., Peugeot, C., Seidel, J.-L., Demarez, V., Le Dantec, V., Seghieri, J., Bariac, T., Biron, P., Richards, P., Afouda, A., Descloitres, M., Legchenko, A., Robain, H., Camerlynck, C., Ottlé, C., Zin, I., Zribi, M., Jacquin, F., Kamagate, B., Lawin, E., Le Lay, M., Varado, N., and Zahiri, E. P.: Caractérisation des processus hydrologiques sur le super-site de la Donga. Haut bassin de l'Ouémé (Bénin), ORE AMMA-CATCH, Atelier Expérimentation et Instrumentation, INSU, Paris, 23–24 March 2004.

Speers, D. D.: SSARR Model, in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resour. Publications, Highlands Ranch, Colorado, pp. 367–394, 1995.
Sugawara, M.: Tank Model, in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resour. Publications, Highlands Ranch, Colorado, pp. 165–214, 1995.
Tarboton, D. G.: A new method for the determination of flow directions and contributing areas in grid digital elevation models, Water Resour. Res., 33(2), 309–319, 1997.
Varado, N.: Contribution au développement d'une modélisation hydrologique distribuée. Application au bassin versant de la Donga, au Bénin, PhD Thesis, Institut National Polytechnique de Grenoble, 310 pp., 2004.
Varado, N., Braud, I., Ross, P. J., and Haverkamp, R.: Assessment of an efficient numerical solution of the Richards equation on bare soil, J. Hydrol., in press, 2005a.
Varado, N., Braud, I., and Ross, P. J.: Development and assessment of an efficient numerical solution of the Richards' equation including root extraction by plants, J. Hydrol., in press, 2005b.
Wubda, M.: Reconnaissance géophysique du bassin versant d'Ara, Mémoire de DESS de Géophysique Appliquée – Université Pierre et Marie Curie, Paris, 2003.
Zehe, E., Maurer, T., Ihringer, J., and Plate, E.: Modeling water flow and mass transport in a loess catchment, Phys. Chem. Earth, Part B: Hydrology, Oceans and Atmosphere, 26(7–8), 487–507, 2001.
Zhang, G. P., Fenicia, F., Rientjes, T. H. M., Reggiani, P., and Savenije, H. H. G.: Modeling runoff generation in the Geer river basin with improved model parameterizations to the REW approach, Phys. Chem. Earth, 30(4–5 SPEC. ISS.), 285–296, 2005.

HESSD

2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

Table 1. Data and sensors used on the Donga catchment.

Data type	Material	Localisation	Measure period	Type	Temporal sampling
	Raingauge	Donga catchment (Fig. 2).	since 1998 (10) since 2002 (11)	Elsyde Œdipe (12) OTT 250 (4) OTT 1000 (5)	5 min
Meteorological data	Air temperature and humidity sensor	Djougou	since 2002	Vaisal HMP45C	15 min
	Pyranometer (Rg)	Djougou	since 2002	Kipp & Zonen SP-Lite	15 min
	Radiometer (Rn)	Djougou	since 2002	Kipp & Zonen NR-Lite	15 min
	Wind monitor (speed and direction)	Djougou	since 2002	Campbell 05103	15 min
	Barometer	Djougou	since 2002	Druck RPT410F	15 min
Discharge	Automatic discharge gauge	Outlet	since 1998	OTT Thalymedes	15 min.+scrutinize
	Automatic discharge gauge	Intermediary stations (Fig. 3)	since 2002	OTT Thalymedes	15 min+scrutinize
Piezometry	Manual record of wells	Cf. Fig. 2	since 1999	Manual reading (6)	3 times a day
	Automatic recordeurs	Cf. Fig. 2	since 1999	OTT Thalymedes (12)	15 min+scrutinize
Soil humidity	Hydric budget: tensiometers, soil humidity and temperature sensors	2 stations	since 2003 since 2004	tensiometer: Watermak Capacitive sensors CS516	hour+scrutinize

EGU

HESSD
2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

Table 2. Rainfall and runoff characteristics for the period 1998–2002.

	Rainfall in Djougou (mm)	Mean rainfall on the catchment (block kriging) (mm)	Annual runoff (mm)	Runoff coefficient
Mean 1925–1984	1336			
1998	1349	1392	413	30%
1999	1373	1423	345	24%
2000	1283	1071	262	24%
2001	1170	1125	217	19%
2002	1153	1016	149	15%

EGU

Table 3. Unknowns of the mass balance and momentum balance equations for each zone.

Zone	Mass balance	Momentum balance
S	y^s: mean depth	v^s: mean velocity
U	s^u: mean degree of saturation	v^u: mean velocity
R	m^r: mean cross section area	v^r: mean velocity
O	y^o: mean depth	v^o: mean velocity
C	y^c: mean depth	v^c: mean velocity

HESSD
2, 2349–2391, 2005

HESSD

2, 2349–2391, 2005

Table 4. Input data and parameters needed for the REW-v4.0 model.

Category	Symbol	Name	Remarks
Input	I_{rain}	Rain	Daily time step
	ETP	Potential evapotranspiration	Daily time step
BC	z^s	Mean depth of the bedrock	Geology map not available on the donga catchment
	b_{flux}	Boundary flux for Zone S	Every boundary is supposed to be permeable
IC	s^u	Initial degree of saturation in zone U	3 iterations in order not to be influenced by initial conditions
	y^s	Initial position of watertable, zone S	
	y^r	Initial water depth in zone R	Start simulation on the 1st January, no discharge
Soil/Zone U parameters	λ	parameter of the Brooks and Corey equation	Use of infiltration measures at the soil surface
	h_e	Air entry pression in the Brooks and Corey model	
Soil/Zone U and Zone S parameters	θ_s	Soil moisture at saturation	Use of infiltration measures at the soil surface
	K_s	Hydraulic conductivity at saturation	
Zone R parameters	K_s^r	Hydraulic conductivity	Table (e.g. Chow et al., 1988)
	n^r	Manning-Strickler coefficient	Table (e.g. Chow et al., 1988)
Surface parameters	n^c	Manning-Strickler coefficient	Table (e.g. Chow et al., 1988)

Table 5. Efficiency for each year, on the daily, decadal or monthly root-squared discharge, 2nd and 3rd order.

	2nd order			3rd order		
	day	decade	month	day	decade	month
1998	0.58	0.66	0.74	0.56	0.59	0.65
1999	0.58	0.63	0.67	0.55	0.59	0.61
2000	0.50	0.63	0.68	0.44	0.52	0.56
2001	0.55	0.61	0.66	0.47	0.51	0.53
2002	0.48	0.52	0.55	0.43	0.43	0.45
Validation 1998–2002	0.55	0.62	0.70	0.51	0.55	0.58

HESSD

2, 2349–2391, 2005

HESSD

2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

Table 6. Efficiency on root-squared daily discharge at every station in 2002, 2nd and 3rd order.

Station	Drainage area (km^2)	2nd order	3rd order
Ara	12.8	0.45	0.14
Bokpérou	17.4	0.21	0.26
Route de Kolokondé	105	0.42	0.59
Koua	292	–3.08	0.51
Nékété	409	0.51	0.60
Donga_Pont	586	0.48	0.43

Table 7. Influence of rain distribution on daily, decadal and monthly efficiency.

Efficiency	rainfall	2nd order	3rd order
Daily	distributed	0.50	0.45
	homogeneous	0.48	0.43
Decadal	distributed	0.55	0.45
	homogeneous	0.52	0.43
Monthly	distributed	0.58	0.47
	homogeneous	0.55	0.45

HESSD

2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

Table 8. Efficiency on root-squared daily discharge at every station in 2002, when the precipitation is distributed or not.

	3rd order		2nd order	
	distributed	homogeneous	distributed	homogeneous
Donga	0.45	0.43	0.51	0.48
Ara	0.16	0.14	0.44	0.45
Bokpérou	0.23	0.26	0.22	0.21
Kolokondé	0.60	0.59	0.42	0.42
Koua	0.51	0.51	−3.08	−3.08
Nékété	0.61	0.60	0.54	0.51

HESSD
2, 2349–2391, 2005

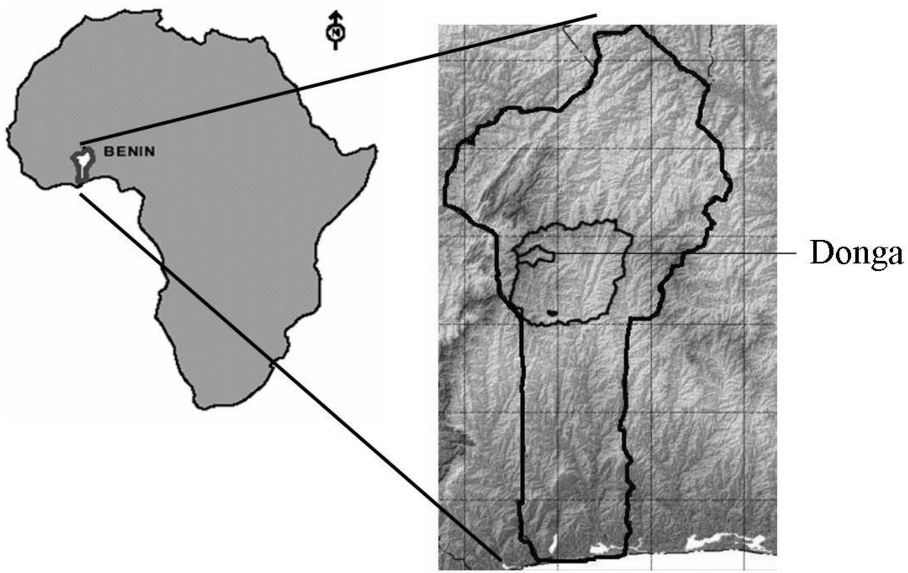

Fig. 1. Situation of the Donga catchment in Benin, Africa.

HESSD
2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

EGU

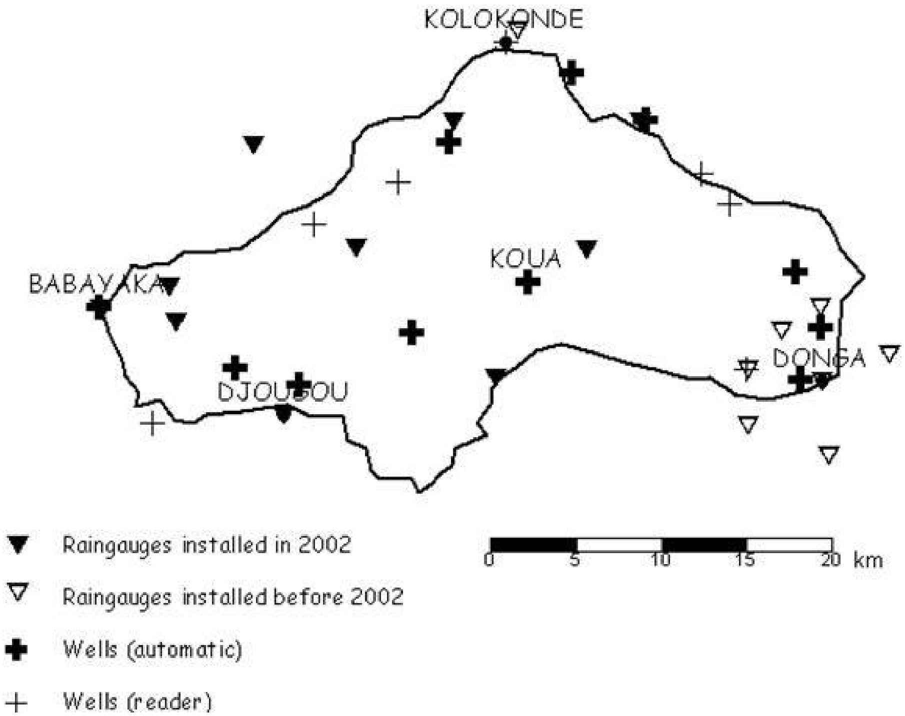

Fig. 2. Network of raingauges and wells on the Donga catchment.

Fig. 3. 6 gauged stations and their drainage area.

HESSD
2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

EGU

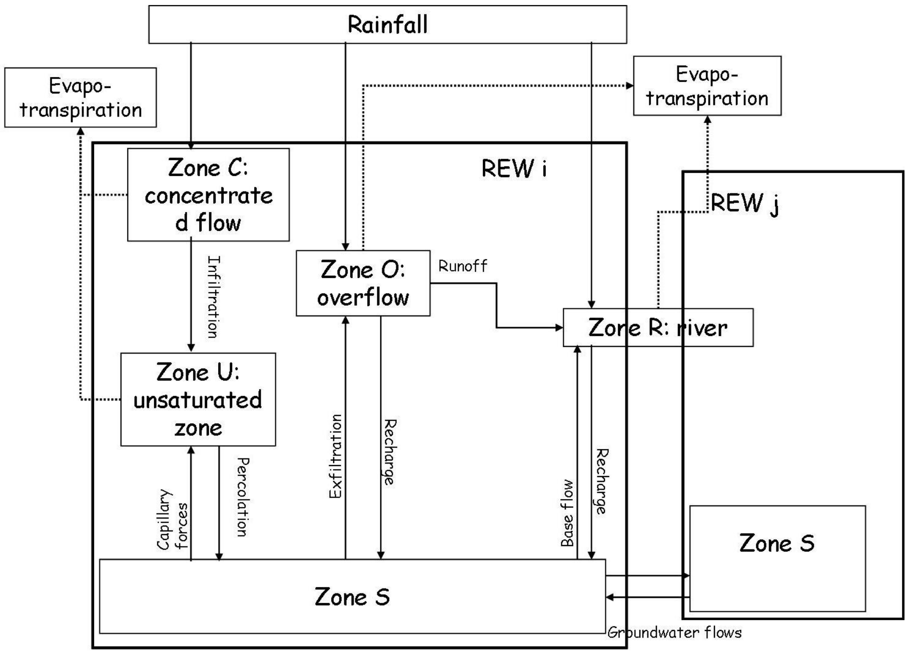

Fig. 4. Schematic structure and exchange fluxes in the REW model.

HESSD
2, 2349–2391, 2005

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀ ▶▶
◀ ▶
Back
Close
Full Screen / Esc
Print Version
Interactive Discussion

EGU

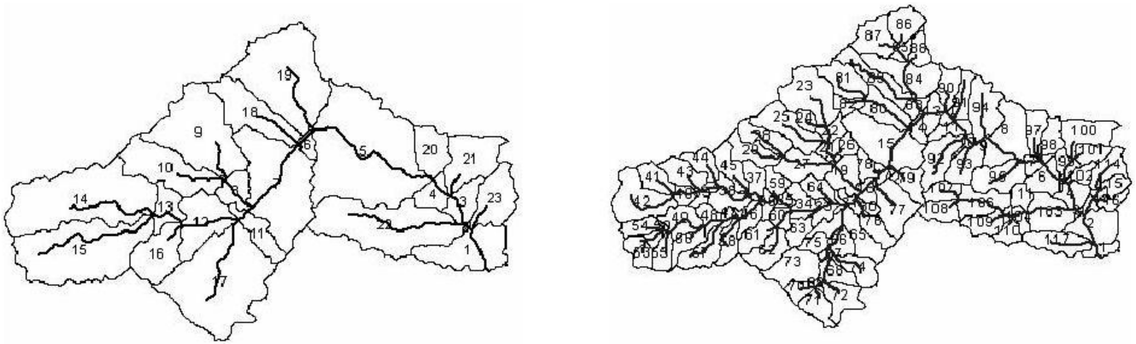

Fig. 5. Two spatial discretisations: 3rd order (23 REWs) and 2nd order (117 REWs).

HESSD

2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

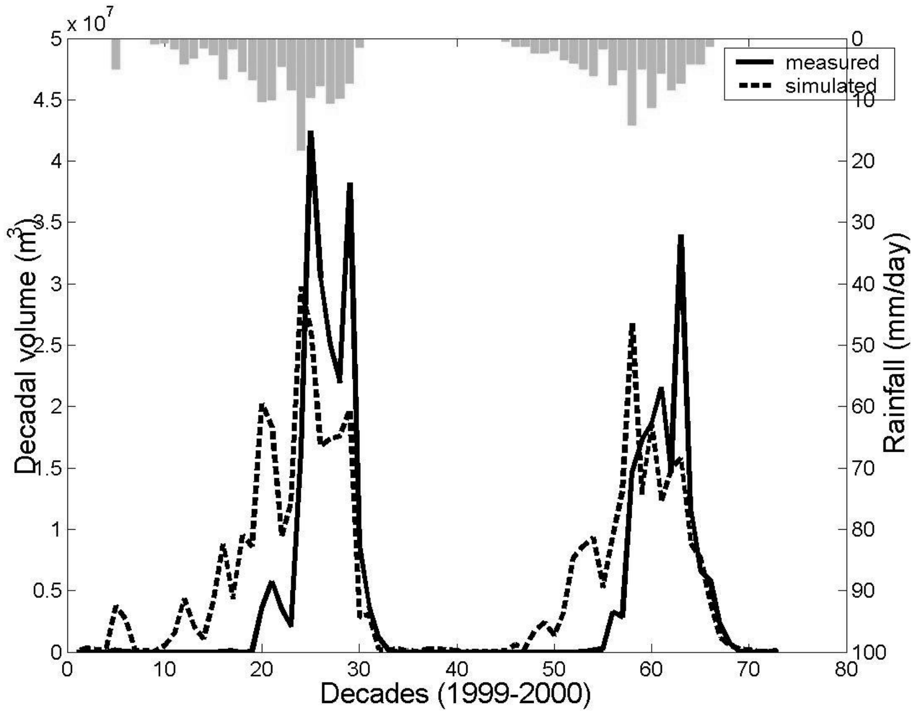

Fig. 6. Decadal discharge at the outlet in 1999 and 2000, using the mean soil surface parameter, with a 3rd Strahler order discretisation.

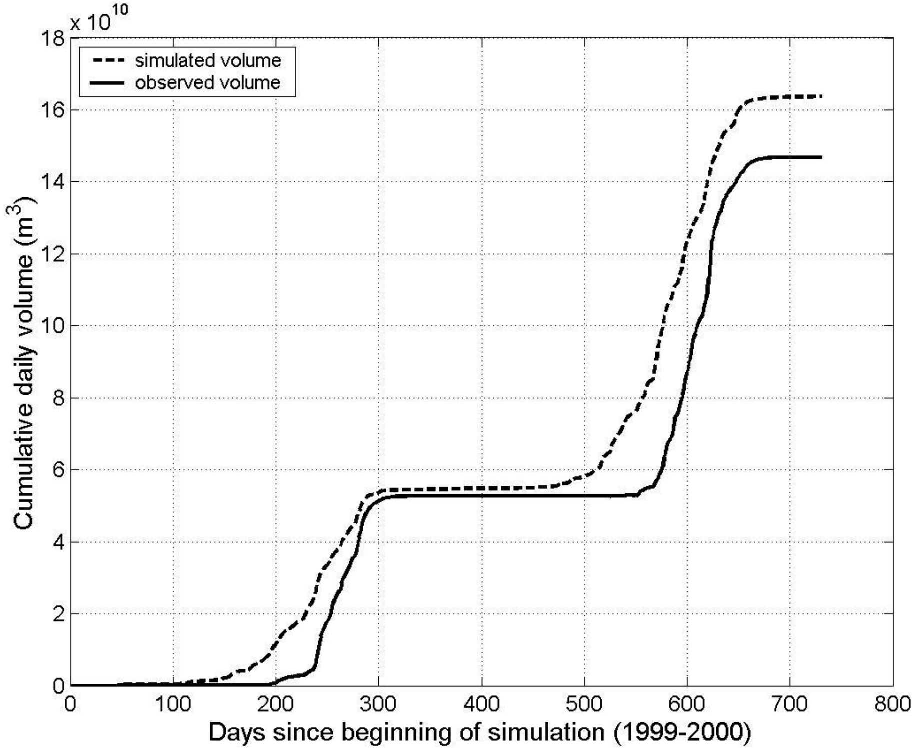

Fig. 7. Cumulative discharge volume at the outlet in 1999 and 2000, using the mean soil surface parameter.

HESSD

2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.

EGU

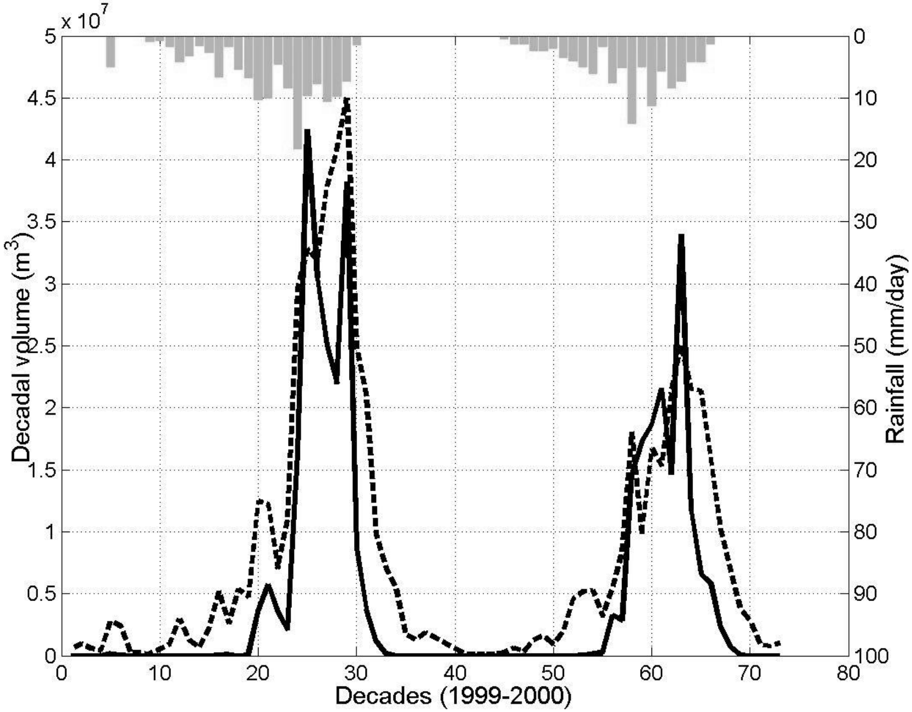

Fig. 8. Decadal discharge at the outlet for the year 1999 and 2000, after adjusting soil parameters, with a 3rd Strahler order discretisation.

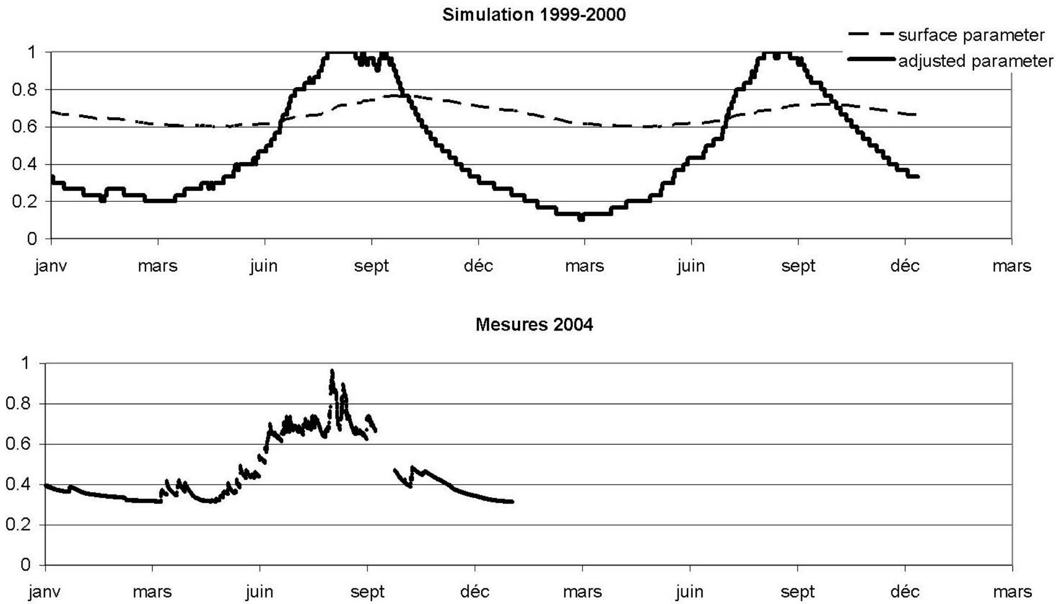

Fig. 9. Soil moisture variations using surface parameter or adjusted soil parameter, compared to soil moisture measurements.

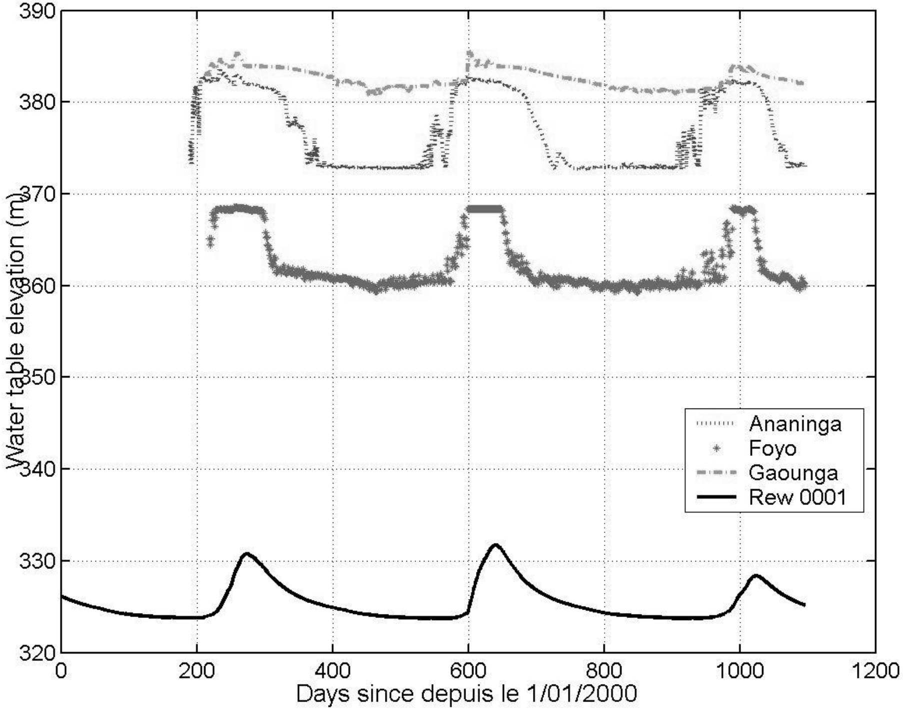

Fig. 10. Groundwater level compared on REW no. 1 (3rd order).

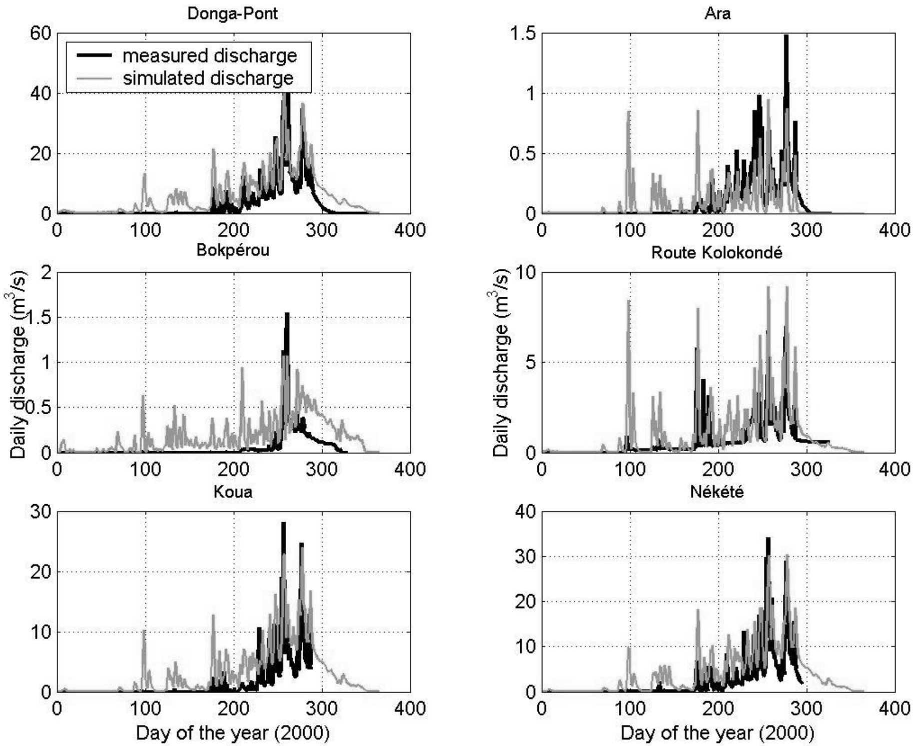

Fig. 11. Simulated and observed daily discharge on the 6 stations for year 2002.

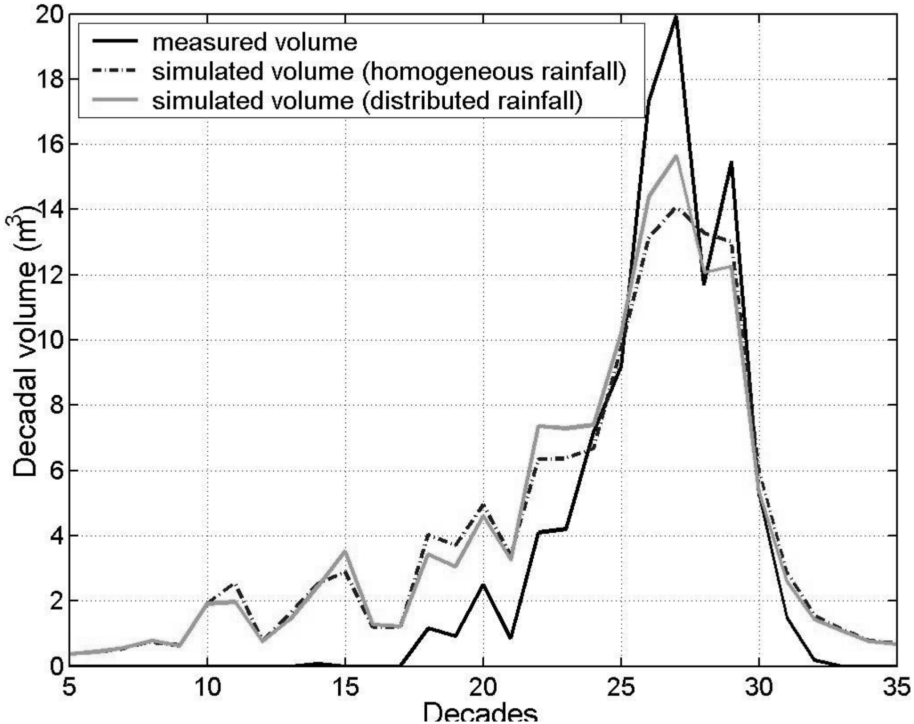

Fig. 12. Decadal volume at the outlet showing the difference between homogeneous rainfall and distributed rainfall.

HESSD
2, 2349–2391, 2005

Evaluation of the REW approach on the Donga catchment, Benin

N. Varado et al.