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A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment

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SUMMARY

This study assesses the suitability of different model types for simulating scenarios of future discharge behaviour in a West African catchment (2344 km^2) in the context of climate and land use change. The comparison of models enables the identification of possible sources of uncertainty in hydrological modelling of a tropical catchment. All models were calibrated and validated for the period from 1998 to 2005 with reasonable quality. The simulation of climate and land use change impacts on discharge behaviour results in substantial differences caused by model structure and calibration strategy. The semi-distributed conceptual model UHP-HRU is shown to be the most suitable for the simulation of current discharge dynamics because the simulated runoff components most closely match the current perception of hydrological processes based on field data interpretation. In addition, the model does not introduce new uncertainties into the simulation by imposing high data demands. All models simulate an increase in surface runoff due to land use change. The application of climate change scenarios resulted in considerable variation between the models and points not only to uncertainties in climate change scenarios but also gives an idea of the possible range of future developments. Overall, this study indicates that the major weakness of all hydrological models is their poor representation of the catchment's soil characteristics and flow processes.

1. Introduction

West Africa and, in particular, the Republic of Benin suffer from a large discrepancy between the amount of renewable water resources and the availability of water for domestic, agricultural and industrial purposes. This discrepancy is the result of physical, socio-economic and institutional constraints (Hadjer et al., 2010). The physical constraints arise from the seasonality of the discharge, a result of the yearly shift between the dry and wet seasons, whereas the socio-economic and institutional limitations imply an infrastructure that cannot make sufficient use of the amount of available freshwater. Apart from these limitations, climate and land use change already have a large impact on the hydrological cycle in West African countries (Giertz et al., 2010; Kasei, 2010; Götzinger, 2007; Jung, 2006; Busche et al., 2005). In view of these challenges and the importance of reliable data on water availability, a proper estimation of the yearly water balance requires the application of hydrological models.

For more than a decade, a large number of modelling approaches have been applied to tropical catchments. Examples are the study by Andersen et al. (2001) on the Senegal River Basin, the study by Güntner (2002) on a catchment in north-eastern Brazil and the study by Leemhuis et al. (2007) on a catchment in Indonesia. The number of modelling efforts has increased rapidly since 2004, with studies undertaken in the White Volta Basin (Kasei, 2010; Jung, 2006; Wagner et al., 2006; Ajayi, 2004) and the Ouémé Catchment (Benin) (e.g., Götzinger, 2007) and its subcatchments, including the Donga Catchment (Séguis et al., 2011; Le Lay et al., 2008; Varado et al., 2006) and the Aguima Catchment (Bormann et al., 2005; Giertz et al., 2005), as well as studies that compare simulation results for different catchments (Giertz et al., 2010; Hiepe and Diekkrüger, 2007; Bormann and Diekkrüger, 2004).

The simulation results of the previously cited studies show that the calculated fraction of each discharge component depends on the model type applied. For example, Hiepe and Diekkrüger (2007) use a time-continuous but semi-distributed model and find that base flow and surface runoff are the dominant discharge components in the Térou Catchment, a tributary of the Ouémé River. In contrast, Giertz et al. (2010) find that interflow is the dominant discharge component in the Térou Catchment by applying a conceptual model. This assumption is supported by electrical

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conductivity measurements conducted by Giertz (2004) and Hiepe (2008) and hydrochemical measurements conducted by Fass (2004), who find that fast runoff components are predominant.

If hydrological models are applied within a single study, model calibration often results in reliable simulations of the past; however, the influence of model choice and model calibration on the simulation of climate and land use change impacts remains unclear, even if uncertainties (e.g., soil (Bossa et al., 2012) and climate (Varado et al., 2006)) are considered.

From a theoretical viewpoint, a physical model represents the underlying hydrologic and land surface processes in greater detail than conceptual or statistical models (Beven, 2001). However, more parameters and greater calibration effort are required as the degree of physical representation of relevant processes in a model increases.

Despite the potential of comparing the results of different models and model types, this method has not yet been widely used in hydrology. For example, Bormann et al. (2009), Huisman et al. (2009) and Viney et al. (2009) apply a multi-model modelling approach to assess the impacts of land use change on the hydrology of a catchment in Germany. To date, no comparative study of model types has been performed for the Térou Catchment, although time-continuous, semi-distributed and conceptually or physically based model types have all been applied to this catchment (Giertz et al., 2010; Hiepe and Diekkrüger, 2007; Sintondji, 2005; Busche et al., 2005; Bormann and Diekkrüger, 2004). The aforementioned studies heavily differed in the simulated fraction of interflow, varying from <3% (e.g., Busche et al., 2005) to 60% (Giertz et al., 2010). Thus, the application of these models in impact studies may yield completely different scenario projections. To differentiate between the effects caused by model choice and the effects caused by climate and land use change impacts, different model types, i.e., physically based and conceptual, are used in this study to improve the understanding of hydrological processes and to provide new insights into the influence of land use and climate change on discharge behaviour.

This paper addresses the uncertainty in discharge modelling of a tropical catchment by comparing simulation results based on different model types. Furthermore, the paper aims to compare the predictions of future discharge obtained by applying land use and climate change scenarios. Towards these aims, four different models were applied to simulate the past (1998–2005) and future scenarios (2001–2049).

2. Research area

2.1. Geographical overview

The Republic of Benin is located in West Africa and extends from the Gulf of Guinea to 12°30′ north and from 0°45′ to 4° east. With an area of 112,622 km^2, Benin is one of the smaller African countries. The Ouémé Catchment drains the major part of Benin. The research area, i.e., the Térou Catchment (2344 km^2), is a subcatchment of the Ouémé Catchment (location and major characteristics shown in Fig. 1).

Benin has a diurnal climate, with a mean annual temperature of 27.2 °C, ranging between 21.9 °C and 32.6 °C (Ermert and Brücher, 2008). There is a strong precipitation gradient of 300 mm/a, with rainfall increasing from northern Benin, which receives 1008 mm/a (period 1961–1990) in a unimodal distribution, to southern Benin, which receives 1309 mm/a in a bimodal distribution (Ermert and Brücher, 2008). Rainfall is primarily generated by squall lines and, to a minor degree, heavy thunderstorms, which form in hot monsoon air masses (Fink et al., 2010).

Fink et al. (2010) note that the high interannual and decadal variability in rainfall intensities and the number of rainy days in Benin can result in severe droughts, such as the one that occurred in the early 1970s and mid-1980s, during which rainfall decreased to a minimum of 800 mm/a. In the Térou catchment, the precipitation distribution is unimodal, with the rainy season occurring between the beginning of May and the end of October and the dry season occurring between November and the end of April. Mean annual rainfall rates vary around 1152 mm, with a maximum rainfall rate of 260 mm in September and a minimum rate of 0 mm in December (Ermert and Brücher, 2008).

Due to millennia-long land use, Benin's potential natural vegetation, i.e., the tropical dry forest, has been replaced by savannah-type vegetation (Anhuf and Frankenberg, 1991). The commonly used classification of Benin's vegetation is based on physiognomic characteristics according to the rules of the 1956 Yangambi Conference (Aubréville, 1957). Based on these rules, the Térou Catchment is primarily covered by savannah vegetation types, whereas 20% of the area is covered by light and dense dry forest. Agriculture only represents 11% of the total land coverage (Judex, 2008).

The land surface of the study area, termed peneplain, was formed by repeating cycles of the pedimentation process (Runge, 1990; Rohdenburg, 1969) creating a specific slope sequence. The upper parts of a slope are covered by iron crusts embedded in stone lines. These structures are layers with an average thickness of 40 cm (Faust, 1991) consisting of coarse material, including angular and curved blocks of quartz (Runge, 1990). The stone lines cover the saprolith, which is a layer a few metres in depth that contains weathered bedrock. The saprolith substrate is characterised by its high clay content.

In the main portion of the slope, the stone lines are overlaid by hillwash sediment. The sediment was formed by bioturbation as a consequence of high termite activity and denudative processes. Due to the translocation of clay, the hillwash sediment is characterised by the soil texture "loamy sand". The lower slope contains a river bed formed by recent fluvial erosion processes (Runge, 1990; Rohdenburg, 1969).

Recent pedogenetic processes are dominated by lessivation (Junge and Skowronek, 2007) and the translocation of iron (Faust, 1991), resulting in small-scale differences in hydrologic processes.

2.2. Land use and climate change

Judex (2008) compares the land use classification for the years 1991 and 2000 for the Upper Ouémé catchment. During this period, the cultivated area expanded by 70%, and the settlement area expanded by 0.8%. In the northern part of the Térou Catchment, the cultivated area increased by 61–100%, whereas it only increased by 21–40% in the southern part. This expansion is the result of migration, agro-colonisation and the vegetation dynamics induced by cultivation practices.

According to Paeth et al. (2008), the future climate of Benin will be characterised by increasing mean annual temperatures (up to 4 °C) and further drying (at least a 25% reduction in mean annual rainfall) until 2050. Christoph et al. (2010) explain the reduction in rainfall by the weakening of the hydrological cycle, especially the recycling of rainfall. They add that the onset of the rainy season will be delayed by more than 10 days by 2025 and that heavy rainfall events will decrease.

2.3. Current perception of hydrological processes

The current perception of the dominant hydrological processes is primarily based on the results of Bormann et al. (2005), Giertz (2004) and Fass (2004). The brief description given here does not include the effect of small-scale inland valleys, locally termed