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Using SIMGRO for drought analysis – as demonstrated for the Taquari Basin, Brazil

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Abstract Tools were developed and tested to quantify space–time development of droughts at the river basin scale. The spatial development of a hydrological drought in river basins brings different challenges to describe drought characteristics, such as: area in a drought and areal expressions for onset, duration and severity. We used the regional hydrological model SIMGRO in a GIS framework to generate the spatially-distributed time series for the drought analysis. Droughts in different hydrological variables (recharge and groundwater discharge) were identified by applying the fixed threshold concept to the time series. The method captures the development of both the duration and the severity of the area in a drought. The GIS helps to better understand the link between areal drought characteristics and spatially-distributed catchment characteristics. Functions, like agriculture, nature or navigation in a region, need to be considered more in defining the appropriate threshold levels. It is also important to take into account varying hydrological conditions like regions with deep or shallow groundwater levels, resulting in periods with capillary rise in the unsaturated zone in the latter.

Key words drought; spatial-temporal; groundwater; surface water; modelling; river basin; GIS

INTRODUCTION

Drought is a natural climate-initiated feature caused by prolonged dry and warm weather conditions, which has large socio-economic and environmental impacts. A drought can develop slowly and imperceptibly and may remain unnoticed for a long time, unlike flood and other natural hazards (Tallaksen & van Lanen, 2004; Tallaksen *et al.*, 2009). Drought affects all components of the hydrological cycle as it develops from lack of precipitation, usually in combination with high evapotranspiration losses. This causes a soil moisture deficit and subsequently leads to reduced groundwater recharge and eventually to lower streamflow. Droughts occur regularly, everywhere across the globe, with significantly different spatial and temporal characteristics (e.g. Sheffield & Wood, 2008). Prediction of the spatial-temporal characteristics of droughts is an essential part of impact assessment for current and future conditions, as part of integrated land and water management. It is important how meteorological drought and its potential changes in the future propagate through the hydrological cycle and develop into hydrological droughts (i.e. droughts in groundwater and surface water).

The objective of our study is: (a) to further develop and test tools that quantify the space–time development of droughts at the river basin scale based upon the approach proposed by Tallaksen *et al.* (2009), and (b) to improve understanding of drought development. The spatial dimension of drought brings different challenges to quantify its characteristics, such as: areal duration, areal severity and area covered by drought. We used the regional hydrological model SIMGRO to generate the necessary time series of hydrological variables for the drought analysis. SIMGRO is incorporated in a GIS, which makes it easier to relate the spatial-temporal characteristics of the different types of drought and to link these to catchment characteristics (e.g. the surface water system). We applied the SIMGRO model to the Taquari River basin, which is part of the Pantanal region (Upper Paraguay River basin, Brazil) to illustrate the methodology development and to discuss the drought-underlying mechanisms. The Taquari River basin has also been selected because water resources are under pressure because of major land-use change.

SIMGRO MODEL

SIMGRO (SIMulation of GROundwater and surface water levels) is a physically-based spatially-distributed hydrological model that simulates regional transient saturated groundwater flow, unsaturated flow, actual evapotranspiration, sprinkler irrigation, streamflow, groundwater and surface water levels as a response to spatial-temporal distributed precipitation, potential evapotranspiration and groundwater abstraction. For a comprehensive description of SIMGRO, including all modules and model parameters, see Querner & Van Lanen (2001) or van Walsum *et al.* (2004).

The hydrological system has to be schematized geographically, both horizontally and vertically, to model regional groundwater flow in SIMGRO. The groundwater system is schematised through a finite element network. The horizontal schematization allows input of different land uses and soils, to simulate spatial differences in the transient evapotranspiration and moisture content in the unsaturated zone. The unsaturated zone is represented by two reservoirs, one for the root zone and one for the underlying soil. For the saturated zone, various aquifers and aquitards can be considered and SIMGRO permits spatially-distributed parameters (e.g. transmissivity) to be specified. In the model, the surface water system is considered as a network of reservoirs. The inflow of one reservoir may be the discharge of the various streams, ditches and surface runoff. The outflow from one reservoir is the inflow to the next downstream reservoir. The stage depends on surface water storage and on reservoir inflow and discharge. In the model, three drainage subsystems are used to simulate the aquifer–surface water interaction. This interaction is simulated for each drainage subsystem using a drainage resistance and the difference in level between groundwater and surface water. Parameters for the drainage subsystems may vary over the modelled area.

The SIMGRO model is used within the GIS environment ArcView. This allows using digital geographical information (e.g. soil map, land use, streams) to be easily converted into model input data. Furthermore, it is extremely valuable for the presentation of the results, but more importantly it helps in the understanding of drought development better through linking drought characteristics to the geo-referenced catchment characteristics.

STUDY AREA AND MODEL SCHEMATIZATION

The Upper Paraguay River basin is used to illustrate the potential of SIMGRO within its GIS environment for drought analysis. The basin is mainly situated in Brazil, but with small tributaries in Bolivia and Paraguay. In this study we focused on the Taquari River, flowing in a westerly direction into the Paraguay River (Fig. 1). The Taquari River has a total length of about 800 km. The upper part of the basin is situated on a plateau, the Planalto, with an elevation of about 200–800 m a.m.s.l. (Padovani *et al.*, 1998). The soils are generally sandy and sandy loam, but in the Lower Taquari they are clayey along the rivers. A study area in the northeastern part of the Taquari River basin (Fig. 1) is selected with an area of 5565 km^2 to study the droughts in more depth. The ground level in the study region varies between 300 and 700 m a.m.s.l., and in general differences between the streams and the adjacent upland are in the order of 100–200 m. The average annual precipitation for the entire basin is 1580 mm, about 80% falls in the wet season between October and March, whereas in the study area the average precipitation is lower, namely 1330 mm/year. In the beginning of the 1990s the cultivated area was about 27% (mainly pasture, soybean and corn), a further 61% is savannah, 7% is wetland vegetation and 5% is woodland. The cultivated land is situated mainly in the high Taquari (Planalto).

The SIMGRO finite element network comprises 9116 nodes spaced about 3500 m apart. We divided the model area into 238 sub-basins, using the main rivers for the flow routing. In the basin an unconfined sandy aquifer with a thickness of 225–570 m overlies impermeable deposits. The transmissivity of the aquifer varies between 150 and 3000 m^2/day. Details about parameters describing the soil and the interaction between groundwater and surface water are given elsewhere (Jonker, 2004). The model has been calibrated based on discharge data from 15 gauging stations for the years 1982–1983 and validated for the years 1985–1986 (Querner *et al.*, 2005).

DROUGHT IDENTIFICATION APPROACH

Droughts were derived from the time series of hydrological variables as simulated with SIMGRO. Most variables are spatially distributed, e.g. actual evapotranspiration, soil moisture, recharge,

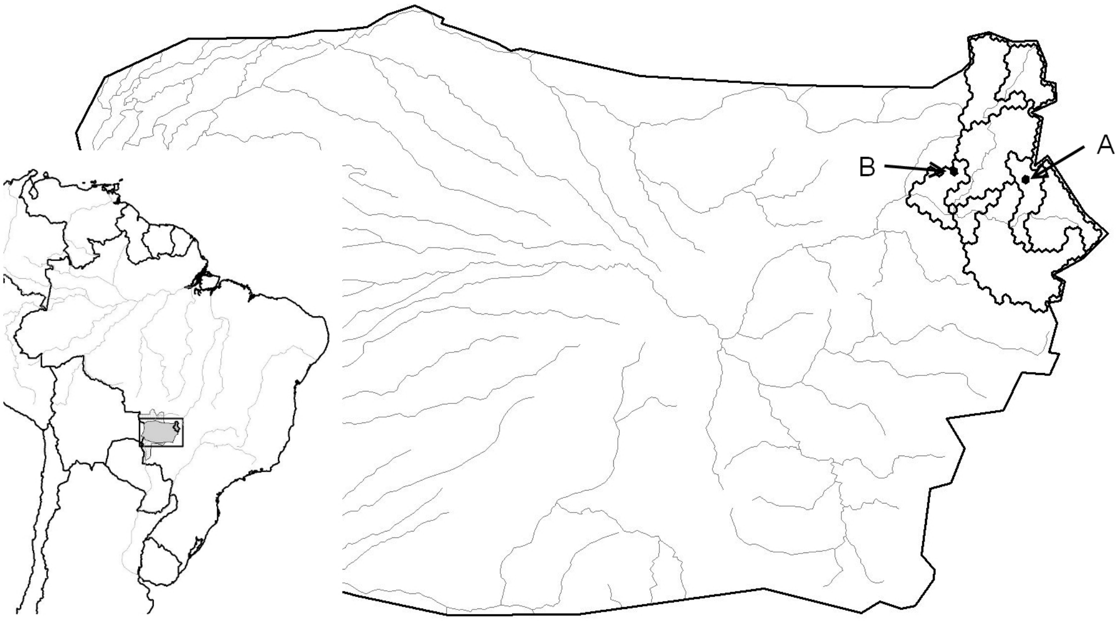

Fig. 1 Location of the modelling area of the Taquari River basin and the study area within the Brazilian part of the Pantanal.

groundwater levels and groundwater discharge. Some other variables are spatially-lumped, e.g. the simulated streamflow, which is available at any point along the river: it integrates the groundwater discharge from the upstream basin. The fixed threshold method (e.g. Hisdal *et al.*, 2004) was applied to each of the time series. When levels of the selected variable are below a predefined threshold, then a drought occurs in that particular variable. In this study the 70% percentile was used, which implies that the variable exceeds or equals that level 70% of the time. Drought studies use percentiles between 70 and 95%, dependent on the objective (e.g. impact on aquatic ecosystem conservation, hydropower generation), to identify drought (e.g. Hisdal *et al.*, 2004). The 70% percentile was chosen to have sufficient droughts for the analysis. For each drought the onset, the duration, the deficit volume and the intensity (deficit volume divided by the duration) were identified as drought characteristics for that particular variable and nodal point. For the calculation of the deficit volume a difference needs to be made between fluxes and state variables. The deficit volume for fluxes is the accumulated difference between the daily fluxes and the threshold, whereas for state variables it is the deviation between the variable and the threshold.

Because droughts are regionally extensive, spatial aspects of a drought such as the area covered and the mean duration or deficit over that area, are important measures of the severity of an event (e.g. Peters *et al.*, 2006; Tallaksen *et al*., 2009). The areal characteristics are calculated by searching for all nodes per time step that are in a drought, considering all at-site drought characteristics. In this study the spatially-distributed drought onset and duration, and the area in a drought were investigated for recharge and groundwater discharge. The daily recharge has been aggregated to weekly and monthly values to ease the interpretation.

RESULTS

The SIMGRO model was run for a period of 25 years (1977–2002) to generate spatially-distributed time series of hydrological variables, among others: recharge and groundwater discharge. The period 1983–1985 for the study area was selected for a more detailed drought analysis, because of its below-average rainfall. It was an isolated multi-year drought, in particular in groundwater. Prior to this period no drought occurred because rainfall was high (an exceptionally wet rainy season in 1981–1982) and the drought ended in the rainy season of 1984/1985 with an average rainfall total.

In the following section drought in groundwater recharge is investigated, together with how spatially-varying conditions like land-use and depth of groundwater table have affected it. Then drought in groundwater discharge is presented.

Groundwater recharge

The monthly average groundwater recharge for two nodes (for location see Fig. 1) are shown in Fig. 2. Location A has deep groundwater levels (~ 20 m–ss) and the land use is soybean. The second node, B, is situated near the river and has shallow groundwater levels (0.2–2.5 m–ss) and the land-use is a semi-open forest. Potential evapotranspiration for soybean is on average 920 mm/year and for the forest 1380 mm/year. For the simulation period of 25 years, the Q70 threshold for the recharge is 0.87 mm/day for location A and 0.13 mm/day for location B. Figure 2 shows the changes in monthly recharge over the study years and the occurrence of the dry season, which is clearly linked to the strongly seasonal patterns of the precipitation. Secondly the amount of recharge reflects the physical properties of the unsaturated zone and the land use (evapotranspiration). A lower recharge than normal during the rainy season, e.g. the year 1983–1984, triggers a groundwater and streamflow drought during the following dry season (see below). For location B the recharge flux is much smaller, because of the shallow groundwater levels and higher actual evapotranspiration. The recharge reaches even negative values, which means that there are periods (e.g. April–May 1983) with capillary rise (an upward flux in the unsaturated zone).

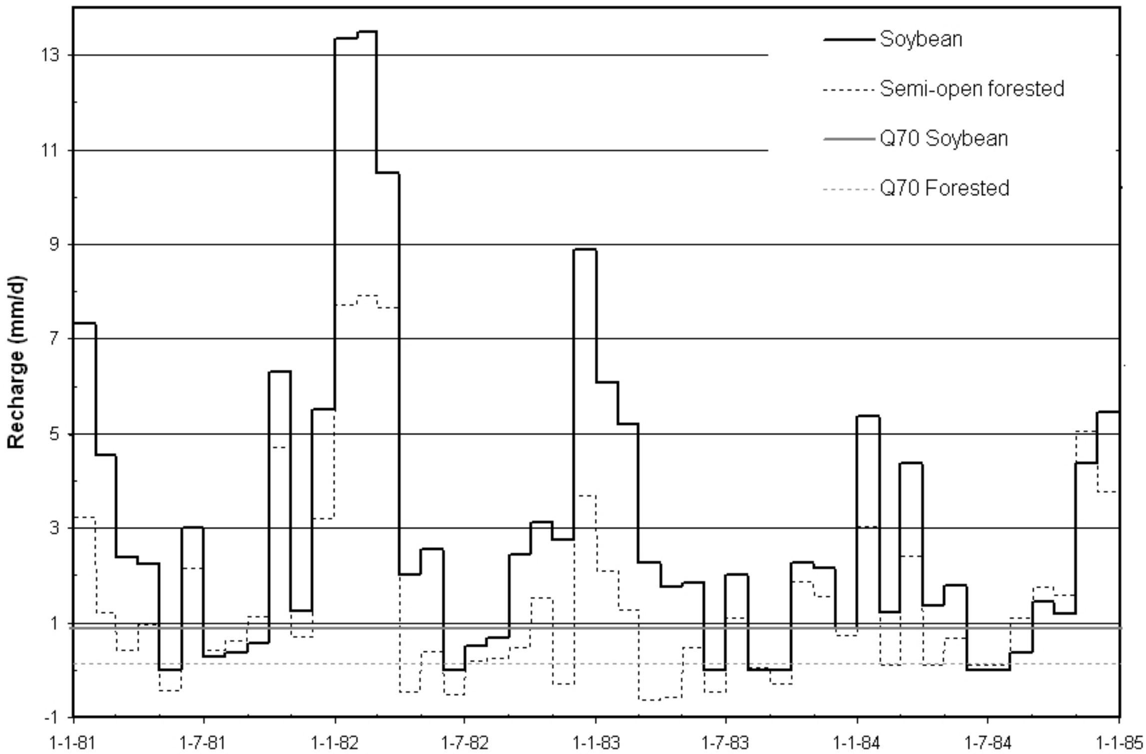

Fig. 2 Average monthly recharge for soybean (A) and semi-open forest (B) and its threshold: Q70 = 0.87 and 0.13 mm/day, respectively, over the period 1980–1985 (locations shown in Fig. 1).

The spatially-distributed onset and duration of the drought in the recharge is presented in Fig. 3. The analysis of drought in groundwater recharge is based on average weekly values to increase the temporal resolution of the data, as opposed to the monthly average values used in Fig. 2. The onset of the drought in recharge is given as a number of weeks after the 20 July 1983. After this date, the first nodes enters the drought (recharge below the threshold value). The onset of the drought (Fig. 3(a)) varies from 1 to 14 weeks. The duration of the drought in groundwater recharge varies from 1 to 28 weeks (Fig. 3(b)). In general for the nodes with deeper groundwater levels, which are found in the east of the study area, the drought starts very quickly (<3 weeks) and the duration of the drought is longer (8–14 weeks). It was found that in the case of the deeper groundwater levels, that such conditions have a more pronounced effect on the onset and duration of the drought than the land use. Long duration droughts can also be found near the river where the recharge is negative (capillary rise) and in some nodes this lasts for 28 weeks. Clearly the recharge flux is below the threshold, which implies a drought in these nodes. However, you can argue if these nodes are really in a drought because groundwater tables are shallow (i.e. capillary rise takes place).

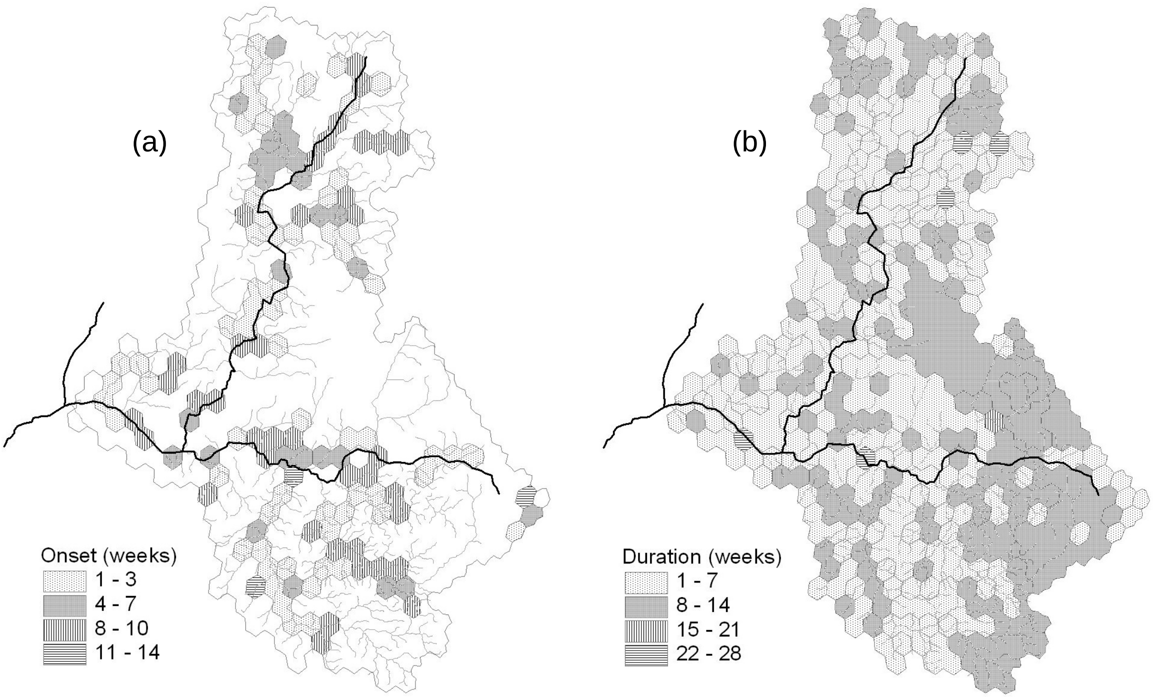

Fig. 3 Drought in the weekly averaged recharge after the 20 July 1983: (a) onset and (b) duration (weeks).

Groundwater discharge

The recharge fluxes and patterns (Fig. 2) cause fluctuating groundwater levels and a groundwater flow towards lower regions where it discharges into the surface water. The groundwater discharge and its patterns are shown for the 1 July (Fig. 4(a)) and for the 1 October 1983 (Fig. 4(b)). During this drought period in 1983 the draining area (i.e. nodes where groundwater discharge takes place) decreases only a bit, due to a decline in the groundwater table. The changes in discharge rate can be noted from the difference between the two dates. Clearly, the reduction in groundwater discharge causes the river flow to decline implying that a drought in streamflow develops. Furthermore, it should be noted that no groundwater discharge exists in large parts of the study area. The smaller streams are dry most of the year, because groundwater levels are all year round below the drainage base as a consequence of the large differences in ground level elevation over the study area and between the stream and the upland. In 63% of the nodes no groundwater discharge occurs during the simulation period.

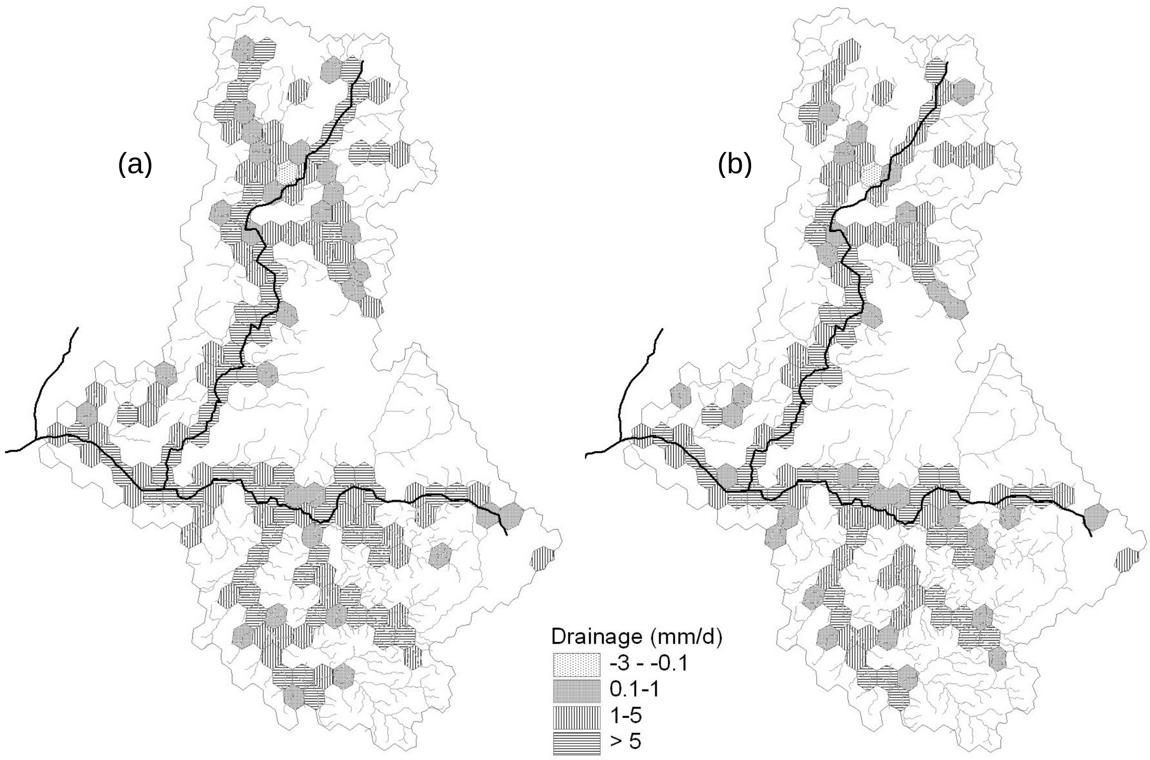

Fig. 4 Groundwater discharge rate (mm/day) during the 1983 drought: (a) 1 July and (b) 1 October.

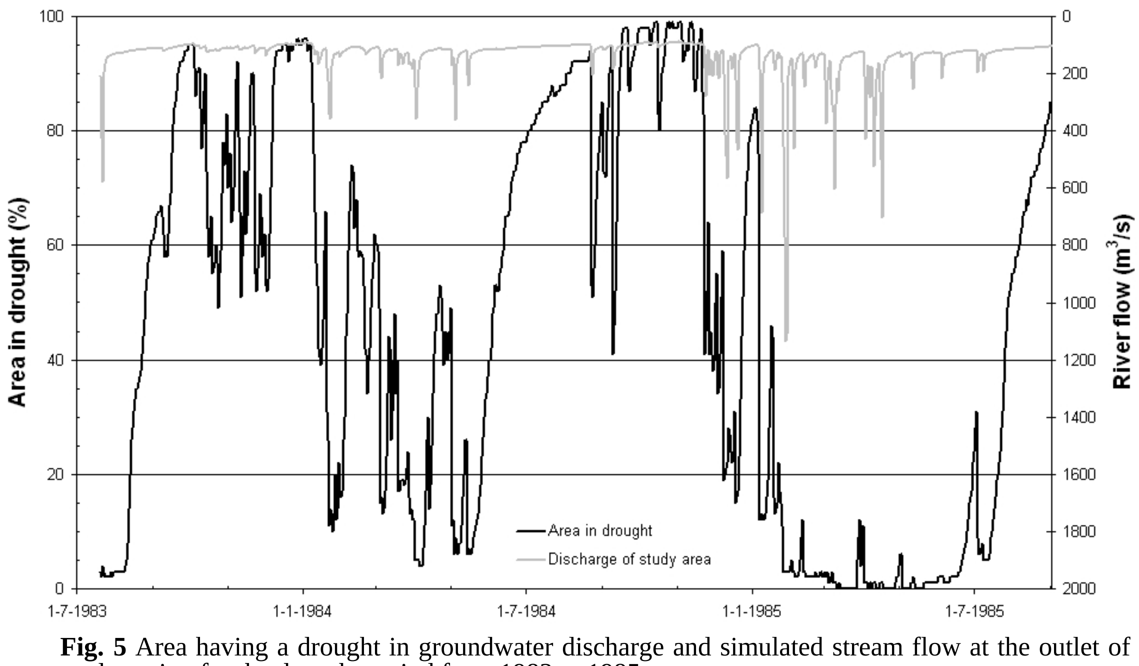

Fig. 5 Area having a drought in groundwater discharge and simulated stream flow at the outlet of the study region for the drought period from 1983 to 1985.

Based on the drought in recharge and changes in groundwater discharge (Figs 2–4), the areal extent of drought in groundwater discharge starting from July 1983 was determined. The period 1983–1985 (Fig. 5) shows two drought events in which an extensive area suffered from drought due to the low groundwater discharge. In the second part of 1983 and 1984 the area in discharge drought reaches a spatial extension of 90% or more. In April 1984 not more of 4% of the area remained in a drought state. Although there are still small scattered areas in drought, these are too limited to consider the drought to be continuous. Tallaksen *et al*. (2009) propose the use of an areal threshold for this reason. In March/April 1985 the drought temporarily diminishes before a new drought starts (Rhebergen, 2009). Clearly, the area in drought is strongly linked to flow in the river (Fig. 5) at the outlet of the study region.

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The study gives insight into the spatial and temporal development of droughts. The results show the spatially-distributed onset and duration of drought in groundwater recharge and associated changes in groundwater discharge. The decrease in groundwater recharge leads to a drought in discharge, which is clearly demonstrated in the temporal evolution of the area in drought (Fig. 5). As demonstrated in this paper transient hydrological conditions are important to consider, e.g. differences in land-use and groundwater table depth attribute to varying evapotranspiration and recharge. The study also shows that a hydrological model incorporated within a GIS makes it easier to relate drought characteristics to spatially-distributed catchment characteristics or associated fluxes.

A physically-based model was used to simulate regional groundwater and surface water flow in basins with spatially-variable land use. Such models have the potential to assess drought conditions within a region, hence focusing on the different functions, e.g. agriculture, nature, navigation and extractions for drinking water. In that respect the SIMGRO model is a powerful tool for modelling drought and producing maps of the different drought characteristics, which can be tailor-made for different functions (e.g. soil moisture drought maps for agriculture or terrestrial ecology, longitudinal profiles along the streams showing drought in groundwater discharge, which are relevant for aquatic ecosystems, navigation, dilution of sewage water or cooling water from power plants.

The potential to use SIMGRO in a GIS environment to study the spatially-varying drought characteristics for different functions urges the need to think about which hydrological variable need to be analysed, but also which threshold to apply. As mentioned above (section on groundwater recharge), one can argue if a drought occurs in recharge if groundwater tables are shallow and capillary rise still occurs. It depends on the function, whether a condition is classified as a drought, e.g. for agriculture the situation with capillary rise might be optimal (no-drought), whereas it already may be too dry for a wetland (drought). Also for navigation it can be indeed considered as a drought, because capillary rise lowers the groundwater level, thus reducing the flow towards the river.

In this study we took the Q70 as fixed threshold, but it needs to be differentiated, depending on the function. For instance from a groundwater resources point of view the threshold for the groundwater recharge could also be given as a constant flux, say 0.5 mm/day, reflecting the minimum water flux needed to replenish groundwater. The threshold can be based on the needed/minimum river flow for navigation or the ecological minimum flow. Using a fixed threshold approach is to some extent rigid. In regions with a pronounced seasonality a variable threshold (e.g. Hisdal *et al*., 2004; Van Loon *et al.*, 2010) might be better to characterize drought for certain functions.

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