Using SIMGRO for flow characterisation of temporary streams, as demonstrated for the Evrotas basin, Greece

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Abstract Tools were developed to quantify space–time development of different flow phases on a river basin scale. Such information is needed for the WFD. The spatial development of temporary streams was investigated in the Evrotas basin, Greece. We used the regional hydrological model SIMGRO in a GIS framework to generate flow time series for all major streams. For a streams reach five flow phases are distinguished, being: floods; riffles; connected flow; pools and dry conditions. For each stream and flow phase, thresholds were identified based on local characteristics. The analysis shows the frequency of the flow phases per month. For all streams in the Evrotas basin the average frequency of the flow phase dry and pools are presented. The aim is that GIS helps to better understand the link between dry streams and spatially-distributed catchment characteristics. Local morphological conditions and roughness of the bed need to be considered in defining appropriate threshold levels for the flow phases.

Keywords temporary stream; flow phases; pools; river basin; SIMGRO model; Greece

INTRODUCTION

Regions with water stress are a recurring and worldwide phenomenon, with spatial and temporal characteristics that vary significantly because of hydro climatic and river basin conditions. The countries around the Mediterranean Sea are characterized by intensive exploitation of the water resources. This results in water scarcity and often a non-permanent flow regime in the rivers and distinct seasonal dry periods. Temporary streams results often in a bad water quality and the disconnected flow sections are even more critical in terms of their ecological status, to be considered for the European Water Framework Directive (Gallart *et al*., 2008). The WFD pays very little attention to intermittent rivers, because water quantity aspects are not directly considered (Vardakas *et al*., 2010). However, water quantity is of great impact on the ecological status of temporal rivers, whether aquatic species can survive or die out, and whether they are able to re-colonise river branches (Skoulikidis *et al*., 2010). The ecological status depends on whether the river bed dries out completely or that pools remain, and how long these dry periods takes place. The presence of pools is very much related to local conditions, like morphology, bed slope, roughness and permeability of the stream bed (Bonada *et al*., 2007).

Within the MIRAGE project (Froebrich *et al*., 2010) research is carried out to give a framework for managing the Mediterranean water bodies dominated by temporary streams. A method needs to characterize the actual spatio-temporal distribution of water under different flow phases at the sub-basin scale. Based on the flow frequency analysis, Gallart *et al*. (2011), proposed a method for a classification considering field observations and discharge measurements. Such information at the point scale, being a gauging station, are often insufficient to describe the actual water availability and ecological status across sub-basins in dry periods. Hydrological models can support the determination of the ecological status of temporary streams within sub-basins. In this study, next to observed time series, we use the regional hydrological model SIMGRO to generate the necessary river flow data. The model is spatially-distributed and physically-based, simulating groundwater and surface water flow. SIMGRO is incorporated in a GIS, which makes it easier to relate the spatial-temporal characteristics of the different types of flow statuses and to link these to catchment characteristics. We applied the model to the Evrotas basin in Greece, to illustrate the methodology development and to discuss the underlying mechanisms. The Evrotas River basin has also been selected because water resources are under pressure due to the increase in agriculture and irrigation over the past 50 years.

The objective of our study in the Evrotas basin is to illustrate the space–time characterisation of river flows focussing on temporary streams at the river basin scale. It uses the approach proposed by Gallart *et al*. (2011) in order to classify different flow regimes in Mediterranean rivers. The spatial dimension of intermittent streams brings different challenges to quantify its characteristics, such as the duration and areal severity of dry streams. Examples of the analysis will be shown that aim at a better understanding of spatial variability of intermittent streams and their changes under human influences. The approach visualizes spatial-temporal variability of the different conditions in the river basin to assist in defining the ecological status. Such information is needed to set targets for sustainable use of the water resources.

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, irrigation, stream flow, 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 (1997) and a case study in a river basins Querner & Povilaitis (2009).

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. Furthermore, snow accumulation and melting has been accounted for in the model, based on the daily average temperature.

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 temporary flows in streams through linking flow regimes to the geo-referenced catchment characteristics.

STUDY AREA AND MODEL SCHEMATIZATION

The Evrotas River basin is situated in the south of Peloponnese, Greece. The river has a catchment size of 2410 km^2 (Fig. 1). The main river has a length of about 90 km (Nikolaidis *et al*., 2009) and flows southwards into the Laconian Gulf of the Mediterranean Sea. The Evrotas basin is bordered in the east and west by mountain ridges, up to 2400 m a.m.s.l. The soils in the basin consist of limestone, schist and karst (Vernooij *et al*., 2011). The valley is filled with fluvial sediments. Karstic aquifers are responsible for the springs that characterize the Evrotas basin. Land use in the area is 38% cultivated, predominantly with olives and oranges. Urban areas cover about 1% of the basin. The remaining area has natural vegetation. The area under irrigation has grown strongly during past decades.
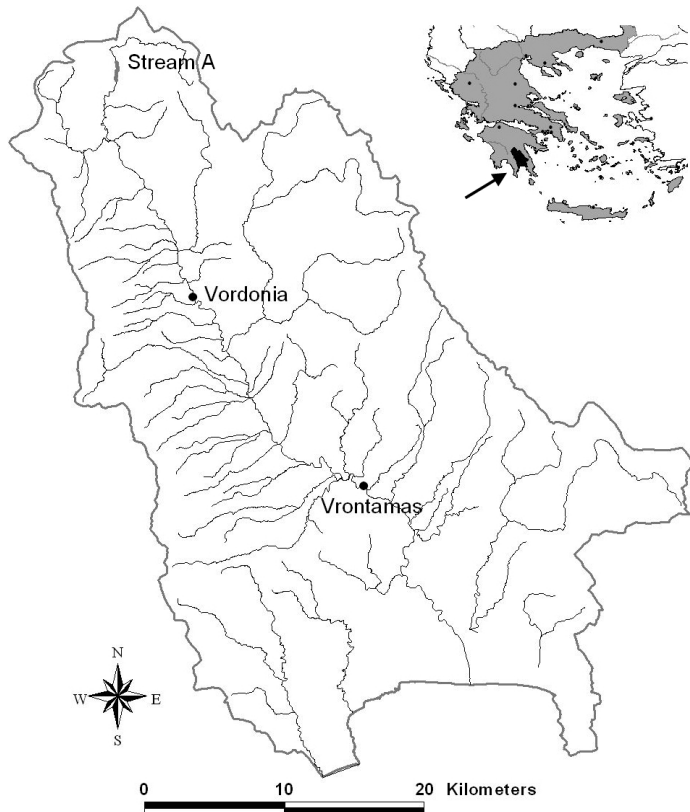
Fig. 1 Location of the Evrotas basin in Greece and the major streams.

The mean annual discharge of the Evrotas is 3.3 m^3/s (1974–2008) as measured at the gauge near Vrontamas (for location see Fig. 1). The Evrotas River is, in some parts, a temporary river, it falls dry for several months. Tributaries are commonly temporary streams. An important factor in the decrease in water availability is the intensive agricultural water use. The Evrotas basin has more than 3600 wells, which extract water for irrigation, industries and drinking water. Therefore the groundwater table has been lowered dramatically due to the exploitation of the groundwater resources.

The mean annual precipitation period, 2000–2008, is 803 mm (Vardakas *et al*., 2010). The majority of the precipitation occurs during the autumn and winter seasons. The summers are dry with a rainfall of about 5–10% of the yearly amount.

For the schematisation of the groundwater system in the Evrotas basin the finite element network considers 13 424 nodes spaced about 500 m apart. We divided the model area into 544 sub-basins, using the main streams for the flow routing. For the basin we considered alluvium, limestone, karst and schist arranged over three layers with a thickness of 50–100 m. The transmissivity of the aquifer was based on the geological map and expert judgement; it varies between 0 and 150 m^2/day. Further details about parameters describing the soil and the interaction between groundwater and surface water are given elsewhere (Vernooij *et al*., 2010).

The model has been only calibrated based on discharge data from five gauging stations for the years 2004–2008. The calculated and measured discharges correspond reasonably well, especially for the lower flows (flows < Q_{50}). As an example, Fig. 2 shows the comparison for the gauge at Vordonia, where frequent discharge measurements were available, particularly for the lower flow conditions. The irrigation for agriculture is one of the major factors influencing the low flows. Using an irrigation intensity of 3.6 mm/d during the summer period resulted in the smallest differences between calculated and measured discharges. This irrigation intensity was in the range of values reported for the basin (Vernooij *et al*., 2010).

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FLOW CHARACTERIZATION

To obtain the flow characterisation of all streams, model results of daily simulated flows were used from the SIMGRO model. The classification proposed by Gallart *et al.* (2011), based on field observations and discharge measurements, was adopted. The flow duration curve is derived from the time series of simulated streamflows. For a streams reach one can basically observe five situations: floods; riffles; connected flow; pools and dry conditions. The description of these flow statuses are given in Table 1. The adopted basic thresholds for the flow situations in the Evrotas basin are also given in Table 1. The thresholds vary between 10 and 75 l/s. For the threshold of floods the stream flow higher than the Q_8 (flow exceeding in less than 8% of the time) has been considered. The assumptions presented in Table 1 are rigid and cannot be applied to all streams in a basin. The magnitude of the flow will differ for each stream reach depending on factors like stream width, bed slope, channel roughness and morphological conditions. Therefore the thresholds should also consider these local indicators, at present being the width and bed slope of the stream. A multiplication factor in the range of 0.8–3.0 considers the indicators and gives the actual thresholds per stream section.

For the gauge Vrontamas, as shown in Fig. 1, the flow phases based on field observations were compared with the approach presented in this paper, and they compare reasonably well.
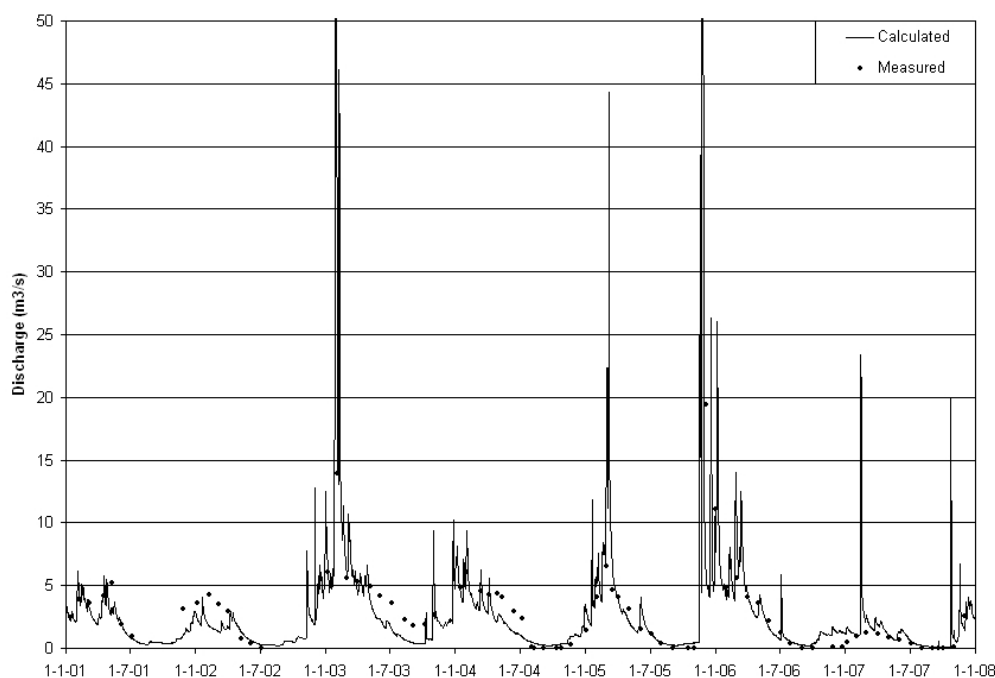

Fig. 2 Comparison of measured and simulated discharges at the gauge near Vordonia (for location see Fig. 1).

Table 1 Basic flow characterisation thresholds adopted for classification of model results for the Evrotas basin.

Flow phases	Description	Flow thresholds (l/s)
Floods	high flow condition, movement of bed sediments occurs	$> Q_8$
Riffles	gradient and morphology give abundant riffles	$< Q_8$ and > 75
Connected	abundant pools generally connected by slow flow	< 75 and > 15
Pools	abundant pools, flow connection between them is rare	< 15 and > 10
Dry stream	stream channel is dry and pools occur infrequent	< 10

RESULTS

The SIMGRO model was run for a period of 9 years (2000–2008) to generate daily discharges for each stream. For a stream reach the flow duration curve is calculated, and depending on local conditions, the thresholds for the different flow phases are defined. The resulting flow characterisation is given in Fig. 3 and shows the frequency of the flow phases per month. Particularly between June and November the stream can be dry as much as 40% of the time. The phase pools occurs mainly in autumn. From November to July the reach has flowing conditions. The flood phase occurs about 20% of the time from December to April. For this reach the stream is dry for only 5 consecutive days in 2003 and 103 days in 2004.
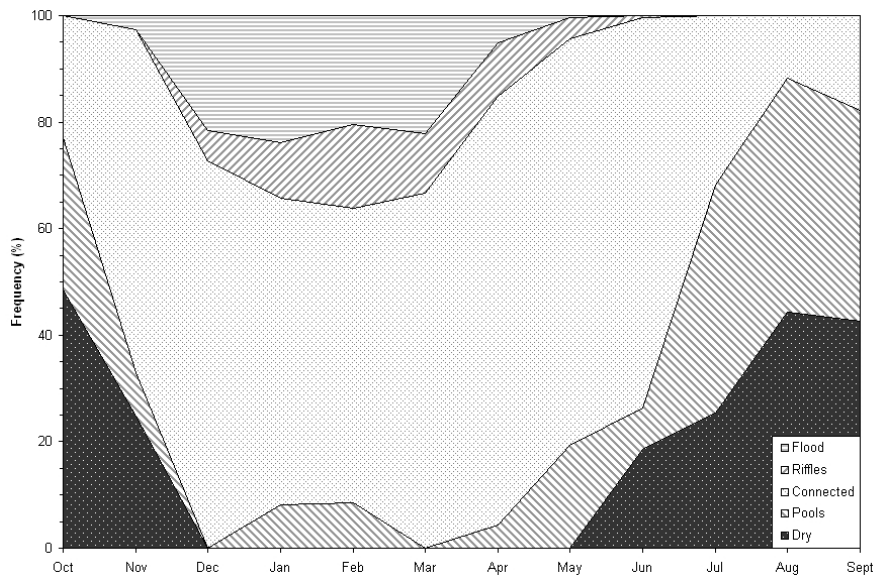

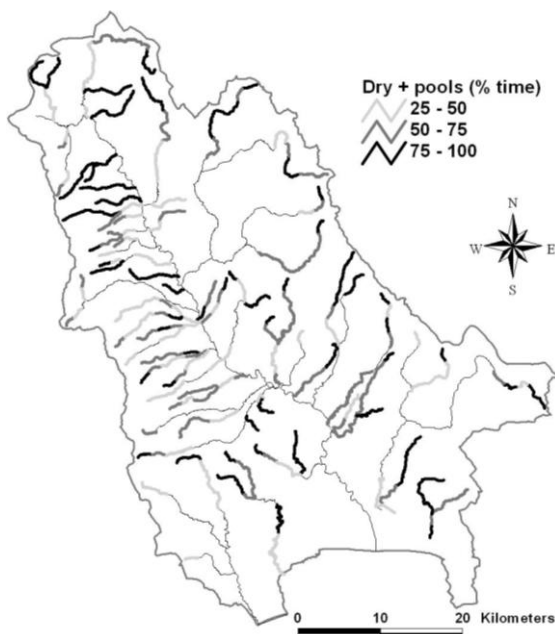**Fig. 3** Frequency of the considered flow phases for stream reach A (for location see Fig. 1)

Fig. 4 Average frequency of the flow phases dry and pools for all major streams in the Evrotas basin, based on results of the SIMGRO model (simulation period 2000–2008).

Within the GIS user interface the above analysis is carried out for all streams, 544 in total. Figure 4 shows for all the streams in the Evrotas basin the average frequency of the flow phases dry and pools. Based on the average frequencies shown in Fig. 4, it appears that the main stream does not become dry. For all streams the frequency of the flow phases is on average for floods 5%; for riffles 23%; for connected streams 31%; for pools 7% and a dry stream 34%. Such information can be used to derive the ecological status for the WFD.

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The flow status frequency graphs allow a rapid visual assessment of the stream regime, based on model results. From the analysis it appears that all the major streams, as shown in Fig. 4, are on average 34% of the time dry. Spatial differentiation in sub-basins can reveal regions with an excessive exploitation of the water resources. Such information can be used to give indications of the ecological status or to assess the effect of changes in, e.g. land use or climate change. We considered thresholds for each stream based on specific site characteristics. Further improvements are needed to quantify the thresholds for the flow phases to be used, based on a geomorphologic classification and roughness of the stream bed.

A scenario analysis using different levels of water use may reveal the conditions for sustainable use of the water resources. The proposed method can therefore help, not only to identify near-natural flow conditions in an ideal setting, but also to analyse measures to restore the hydrological system. Such assessment is important for heavily modified water bodies (HWMB) in the framework of the development of RBMPs, to reach an increase in flow duration.

Prediction of the spatial-temporal characteristics of droughts is also an essential part of the assessment for current conditions, as part of integrated land and water management. It is important how a meteorological drought propagate through the hydrological cycle and develop into hydrological droughts, e.g. a spatial-temporal analysis of the groundwater drainage or recharge as reported by Querner & Van Lanen (2010). Such information forms also the bases for understanding the spatial-variability of temporary streams.

A physically-based model was used to simulate regional groundwater and surface water flow in basins with spatially-variable geo-hydrological conditions and land use. Such models have the potential to assess temporary stream conditions within a river basin. Hence they focus on the impact of, e.g. agriculture or groundwater extractions, on the extent of temporary streams and thus the ecological status. In that respect the SIMGRO model is a powerful tool for modelling the flow conditions and producing maps of the areal extent of temporary streams. The study also shows that a hydrological model incorporated within a GIS makes it easier to relate flow regime characteristics to spatially-distributed catchment characteristics or associated fluxes.

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