Modelling runoff uncertainties in agricultural catchments using a stochastic vector drainage algorithm and error propagation

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Abstract—**Anthropogenic ditch drainage networks have a strong impact on the runoff of small cultivated catchments and are more and more considered in hydrological modelling. However, maps of ditch drainage networks are not usually available which results in uncertainties of water flow-paths. In this context, this study aimed to assess runoff uncertainties entailed by uncertainties of ditch drainage network. We used a coupling approach to propagate uncertainties generated by a random network generation method in a hydrological model. First, we used a stochastic vector drainage algorithm running within the lattice of the field boundaries valued by elevation. It simulated equi-probable networks on a small cultivated catchment, with respect to morphology and uncertainties of elevation data. A thousand simulations represented uncertainty of the spatial organization and density of the network. Next, we propagated uncertainties of the water flow-paths through the hydrological model MHYDAS. Uncertainty of network runoff was high: the coefficient of variation of total volume was equal to 21% at a sub-catchment scale and equal to 18% at the catchment scale. This uncertainty can be partly related to uncertainty of the network density. In addition to uncertainties of network runoff, uncertainty occurred about diffuse flow-paths too, due to the change of the topology of the fields. This uncertainty of overland flow was higher than for the network (coefficient of variation of overland flow indicator equal to 123%) and closely related to ditch drainage density. Finally, this study (i) proposed a way to map runoff uncertainty at different scales in the case of an unknown actual network, (ii) allowed to evaluate the relative importance of the ditch drainage network in runoff simulations.**

I. INTRODUCTION

Importance of linear elements in cultivated landscapes, such as ditches or hedges, have been highlighted in various natural processes. In hydrology, linear features alter both surface and groundwater hydrology [1]. Therefore, more and more spatially distributed models consider linear features. In hydrological models, mapping the ditch drainage network is required to get confidence in model outputs and to correctly represent connectivity in landscapes [2]. However, the cost of exhaustive ground survey is very high [3] and remote sensing of these elements is not enough accurate yet [4]. In order to get around these difficulties, it is possible to generate random maps of drainage networks [5]. This method allows to test the sensitivity of the model to uncertainty in drainage network mapping. Uncertainty analysis of vector data in spatial modelling is not very usual yet but is encouraged by [6].

Uncertainty propagation of hydrological input has become usual nowadays [7] [8]. However, most of these approaches concerns global parameters or attributes of spatial features, not uncertainty of location nor geometry of objects. Uncertainty in drainage network mapping have been studied by [9]. Nonetheless, uncertainty concerns the exact location of drainage network extracted from a DTM and the error propagation in hydrological simulation isn't carried out. Moreover, for the previous study, natural streams are concerned which implies a difference in scale and a far less important spatial variability. Finally, the aim of this study is to assess the sensitivity of runoff simulation to uncertainty of maps of ditch drainage network, both on channel runoff and on overland flow on the hill-slopes. A specific vector drainage algorithm running within the field boundaries lattice valued with elevation is used, with respect to catchment morphology and uncertainties of elevation data.

II. METHODS

A. General concept: landscape and hydrological models coupling for uncertainty propagation

The general method relied on a coupling between a landscape model and a hydrological model. We used a stochastic drainage algorithm to generate numerous ditch networks which represent uncertainty of network mapping. We used each network in the hydrological model: we computed water flow-paths before to propagate the simulated runoff. We defined several networks and runoff metrics in order to evaluate the runoff uncertainty in line with network mapping uncertainty.

B. Stochastic simulations of ditch drainage networks

The algorithm used to generate ditch drainage network was detailed in [5], so we only describe the main principles below. This algorithm can be seen as a vector drainage algorithm running within the lattice of the field boundaries, with respect to catchment morphology, elevation data uncertainties and a set of observed reaches of the network (natural downstream reaches). Each segment of the field boundaries representing a potential ditch is bounded with two nodes on which elevation is attributed. Consequently, the field boundaries lattice is directed with a unique direction if difference in the altitude of the nodes is greater than an uncertainty parameter dZ related to the noise of elevation data and both direction if not. The method of network generation consists in a stochastic drainage algorithm which generates directed tree network structures corresponding to connected sub-graph of the directed lattice. The method is based on (i) directed random walks within the directed lattice of the field boundaries and (ii) a branching-pruning random process. This process allows simulated networks to converge on a target: total length of network connected to the outlet, etc. Numerous networks can be simulated which allows to represent uncertainty of network mapping. This uncertainty concerns directly the geometry and the density of the network, and indirectly topography of the networks, the connections between fields and ditches and the delineation of subcatchments.

C. Propagation of uncertainty in hydrological modelling

We used each simulated network for a hydrological simulation run. We used the physically based rainfall-runoff model MHYDAS [2]. MHYDAS is a distributed model that discretizes the catchment as a series of interconnected geographical units. Geographical units considered here are fields (surface units) and the ditch network (linear unit).

The first step is to compute the topological relationship between fields and ditches. To achieve this task, the Geo-MHYDAS tool, running under GRASS GIS is used. Geo-MHYDAS builds an oriented topology between irregularly shaped surface units and linear units that allows the routing of the simulated runoff across the landscape [10]. Geo-MHYDAS uses as input a DEM and the GIS layers of the ditch network and of the fields. For each unit, the neighbor with the steepest slope is defined as its downstream unit. Next, MHYDAS simulates Hortonian mechanisms of surface runoff. A Green and Ampt-like ponding time formula determines infiltration rate on fields (surface unit). The rainfall excess is converted in runoff, which is routed to the outlet of the unit (another field or a ditch) thanks to the diffuse wave equation. Then, the diffusive wave equation is used to route the discharge through the network.

D. Descriptive network and runoff metrics

In order to compare runoff simulations with simulated networks and the simulation with the actual network, we defined descriptive metrics of both networks and runoff. Total upstream network length was used to describe the network in a given point. To characterize the spatial arrangement of drainage density, a 500m×500m squared grid was used, and for each cell, the cumulated network length was calculated. Concerning network runoff, we calculated lag time, peak discharge and total volume along the network, while we calculated an overland flow indicator on the hill-slopes. Subcatchment wasn't the appropriate scale to compute overland flow since their delineation wasn't constant between simulations, that's why this indicator was computed on each cell of the mentioned above grid by averaging the overland flow of the hill-slopes inside each cells. Finally, for each metric, difference between the actual network and simulated networks was computed to represent the uncertainty.

E. Case study

1) Study area

The study area is the 6.4km² Mediterranean Bourdic catchment, located in south of France. The altitude varies between 45m at the outlet to 128m westwards. The actual open ditch drainage network is 72 km long and covers all the catchment but the limestone uplands (cuesta).

2) Networks simulations

For each of the thousand simulations, the target total network length was selected randomly between a minimal value (length of natural downstream reaches) and a maximal value (total cumulated length of the field boundaries, i.e. about 220 km). The observed reaches came from French national databases on hydrography (BD TOPO ®, BD CARTHAGE ®), representing in total 10.8 km long reaches). The dZ parameter was fixed to 1m according to the noise of the used 5m resolution DEM on elevation.

3) *Runoff simulations*

Model calibration was performed using common values on the studied area [11]. In order to limit the number of variables tested, a simplified case was studied here. Rainfall was considered as spatially homogeneous and represented by a simple triangular rainfall of 50mm in 4 hours. The parameters of the ditch networks (ditch height, etc.) were assumed as invariant over the catchment. We assumed no interaction between surface and groundwater to focus on surface runoff. A homogeneous land cover was used, which implied identical surface units parameters (hydraulic conductivity for instance).

III. RESULTS AND DISCUSSION

A. *Uncertainty in ditch network mapping*

We simulated a thousand networks, which allowed to represent the maximal uncertainty on drainage density (Fig. 1). Due to the simulation process, simulated networks were on average longer than the actual network (since their length corresponded approximately to half the cumulated field boundaries length).

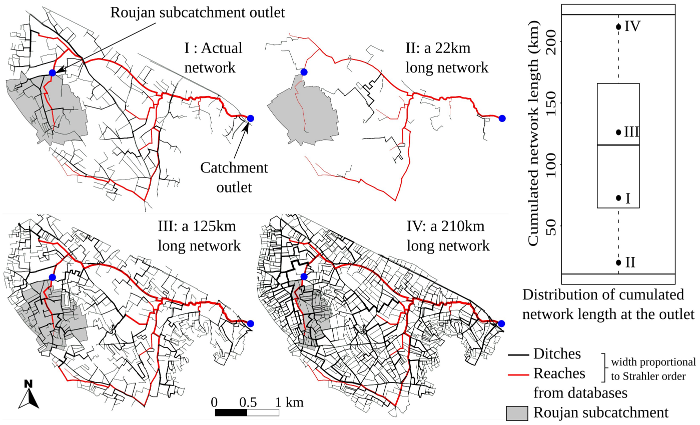

Figure 1. Variability of ditch network length and sub-catchment areas

B. *Uncertainty in network discharge*

We used both simulated networks and the actual network in hydrological modelling. We computed runoff metrics and related them to network length uncertainty (Fig. 2). Peak discharge and total volume difference seemed to be well related to network length difference. The lag time exhibited a more complicated trend. At the outlet, runoff seemed to mainly depend on network length, with a rather low runoff uncertainty range for a given network length. Nonetheless, there was also an uncertainty for a given network length error which meant that other simulated network characteristics, such as slope or topology, influenced runoff uncertainty too.

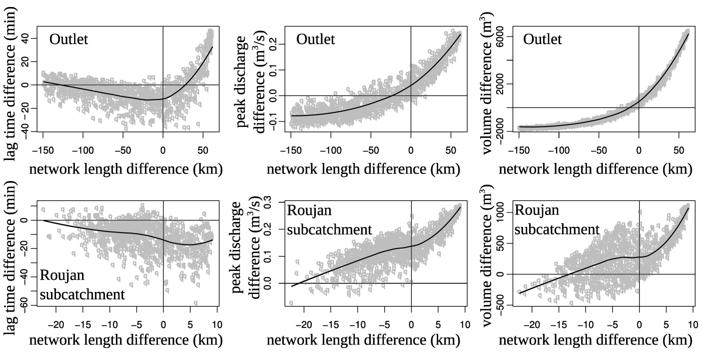

Figure 2. Relation between network length and runoff uncertainties.

Uncertainty was higher at the outlet of a sub-catchment (Fig. 2). For a given network length, there was an uncertainty of upstream drained area too which increased runoff uncertainty. This area uncertainty clearly appeared for the Roujan sub-catchment (Fig. 1).

To focus on uncertainties that did not depend on errors in drainage networks length, we examined simulated networks whose length was more or less 5% equal to the actual network length (TABLE I.). We could see that the bias on hydrological metrics was almost the same, but the uncertainty decreased at the outlet. For instance, there was a 1% bias with a coefficient of variation of 18% on total volume at the outlet with all the networks, in comparison with a 4% bias but with a coefficient of variation of only 2% for the set of networks more similar to the actual one. The bias was assumed to be related to differences in topography and topology of the networks. At the subcatchment scale, the network with high precision in total length did not necessary reduce uncertainty since a precise total length did not ensure an accurate delineation of the sub-catchment area, nor an accurate sub-catchment network length.

Concerning these results about network runoff, a limit should be stressed about the absence of interaction between the ditch network and the groundwater which could modify these trends.

TABLE I. NETWORK RUNOFF UNCERTAINTY

	All networks				**Networks whose length = actual length +/- 5%**			
	Subcatchment		***Outlet***		***Subcatchment***		***Outlet***	
	MPE*	CV*	MPE	CV	MPE	CV	MPE	CV
Lag time	-18%	15%	-1%	4%	-21%	14%	-4%	3%
Peak discharge	35%	17%	2%	18%	39%	11%	9%	6%
Total volume	18%	21%	1%	18%	19%	16%	4%	2%

* MPE: Mean Percentage Error, CV: coefficient of variation

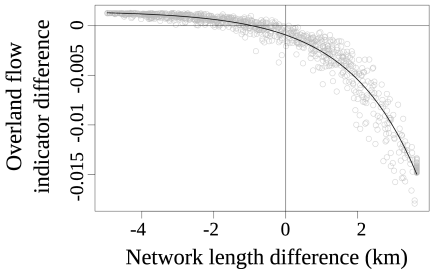

Figure 3. Uncertainty on overland flow for an example grid cell

C. *Uncertainty in hillslope overland flow*

Overland flow on the hill-slopes was also impacted by change in ditch network. Indeed, a ditch intercepted (reduced) overland flow on a hill-slope. We could thus see on Fig. 3, that when we underestimated drainage density on a given area, we overestimated overland flow and vice versa.

On each cell of the grid used to compute overland flow, we fitted a trend line as the one above. The average quality of the fitting could be estimated by the median R^2 equal to 0.96. This good fitting showed how the overland flow as modelled by MHYDAS directly depended on the network length. On TABLE II. , we could see that both the bias and the uncertainty decreased when the uncertainty on network length decreased. The bias was equal to 58% when all networks were considered, with a coefficient of variation of 123%, whereas with the networks whose length was more or less 5% equal to the actual one, the bias was divided by 2 and the coefficient of variation by 6. The bias was assumed to be related with the network spatial distribution. If all ditches were grouped or if they followed the slope direction, they did not intercept overland flow as well as if they would be well distributed and perpendicular to the slope.

IV. CONCLUSION

This study showed how uncertainty of the anthropogenic ditch drainage network mapping with respect to terrain morphology propagated through hydrological modelling. The runoff of a small cultivated catchment was very sensitive to uncertainty of ditch drainage network mapping. Indeed, uncertainty of network mapping caused uncertainty of water flow-paths, both on the fields and in the network. For network runoff at the outlet or for overland flow on hill-slopes, we could easily related this uncertainty to drainage density. For sub-catchment, owing to uncertainty of sub-catchment delineation and area, this relation was less obvious and scale dependent. Moreover, apart from the impact of drainage density, other parameters might be important, such as network slope and topology. Finally, to find out more precisely on which parameters of the networks the efforts should be made in order to accurately simulate runoff, a sensitivity analysis should be carried out.

TABLE II. OVERLAND FLOW UNCERTAINTY IN FUNCTION OF NETWORK LENGTH UNCERTAINTY

	Overland flow indicator	
	MPE*	CV*
All networks	-58%	123%
Networks whose length = actual length +/- 5%	-25%	17%

* MPE: Mean Percentage Error, CV: coefficient of variation

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