Extraction and re-implementation of SWAT-Model calculations under the MAELIA platform in order to simulate the socio-environmental impacts of norms.

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Abstract

MAELIA (Multi-Agent for EnvironmentaL norms Impact Assesment) is an agent-based simulation platform designed to assess the impact of alternative water management policies at the watershed level. It simulates interactions between human activities (agricultural, domestic and industrial withdrawals, regulations of water uses) and ecological processes (crop growth, plant evapotranspiration and water flow). To simulate the water cycles at the sub-watershed level, the representations of hydrological processes in SWAT are analysed and re-implemented in MAELIA.

In this paper, we discussed some of the design choices, simplifications (e.g. overland flow, soil temperature, perched water table and bypass flow are not simulated) and modifications (e.g. different methods of generating HRUs, elevation bands, snow water are calculated in the sub-basin loops etc.) we made in order to integrate SWAT hydrological formalisms: surface-runoff, soil water, snow water, groundwater, evapotranspiration and water-routing. Otherwise, MAELIA use some specific processes for simulating crops growth (Jeud'O model), weather generator (SAFRAN model) and water management (Multi-agents). The MAELIA platform was tested on a 6000 km^2 watershed at the upstream part of Adour-Garonne-Basin in south-west of France for a 10-years period (2000-2009). The results show that the MAELIA platform reasonably reproduces stream flow hydrograph for a long-term simulation, the effects of water management restrictions are well represented, especially during the low-water periods. Sensibility analysis shows that some parameters in MAELIA are less influential comparing with SWAT model (base-flow and soil properties parameters). The MAELIA platform is a promising agent-based, real-time model for simulating the impacts of water management policies including human behaviour and economical aspects.

Keywords: SWAT, water cycle modelling, agent-based simulation platform

1. Introduction

In recent years, hydrologic models have been increasingly used by hydrologists and water resource managers to understand and manage natural and human activities that affect watershed systems(Zhang et al., 2007). Several hydrologic models have been used into the Integrated Assessment Modeling (IAM) platforms and approaches to address sustainability issues and the associated environmental and resources management problems(Jakeman and Letcher, 2003; Pahl-wostl et al., 2000).

The IAM MAELIA platform aims at assessing the environmental, economic and social impacts of various management strategies and policies regarding the management and uses of water resources while accounting for climate changes. This computational multi-agent platform is developed to provide information usable by institutions in charge of designing and implementing sustainable management strategies of water resources at watershed levels, mainly in the Adour-Garonne Basin (AGB), in the southwest of France. In this platform, entities of the investigated water management situation, considered as a "social-ecological system", are categorized into three primary classes: actors, material resources and cognitive resources. Processes that impact or use these entities are classified into four main domains: hydrology, agriculture, normative aspects and the other water users. The whole platform was presented (Gaudou et al., 2013). While behavior of the agricultural and normative processes was the object of specific developments, it was decided to represent surface and groundwater flows through existing and robust formalisms.

During the last decades, various rainfall-discharge models capable of representing hydrological behaviors of a variety of catchments have been demonstrated(Jeong et al., 2010; Long, 2009; Moore, 2007; Moretti and Montanari, 2007; Perrin et al., 2007; Todini, 1996). However, most of the statistically-based rainfall-discharge models were not able to simulate the relative impact of alternative input data such as vegetation and management practices. As the main objective of MAELIA platform is to simulate the interactions between the water resource system and the governance system as well as the users (agricultural, industrial and domestic), a physically-based hydrologic model which could elaborately simulate the water cycle in a river-basin should be integrated into the platform.

The Soil and Water Assessment Tool (SWAT) model(Arnold et al., 1998) is a continuous time, long term yield, physically based model that can simulate surface and subsurface flow, soil erosion and sediment deposition, nutrient fate and movement through watersheds. It has proven to be an effective tool for assessing water resource and nonpoint source pollution problems for a wide range of environmental conditions across the globe. Over 250 peer-reviewed published articles have reported SWAT applications, reviews of SWAT components, or other SWAT related research(Gassman et al., 2007).Besides, SWAT application has been using to analyze the transport of water and nutriments in the AGB for over five years and the present researches gave us promising results (Boithias et al., 2011; Chea, 2012; Oeurng et al., 2011). Therefore, we had decided to mainly analyze the hydrological processes of SWAT model and re-implement the required processes with necessary modifications to the MAELIA platform.

In many recent SWAT related researches, several extensive hydrologic and environmental model have been introduced into the SWAT model, such as the water quality model CE-QUAL-W2(Debele et al., 2006), sub-hourly rainfall-runoff model (Jeong et al., 2010) and agricultural policy/environmental extender model APEX

(Wang et al., 2011). However, few studies have been reported about re-implementing SWAT processes to another model. This current study intent to reuse SWAT hydrological component originally developed in the SWRRB model (1990), and SWAT routing component originally developed in the ROTO model (Arnold et al., 1995). This research enables us to identify the necessary processes to precisely simulate the water cycle at a watershed scale, the stability of the equations and algorithms of SWAT model. We were then developed the calibration procedures coupling the use of SWAT and MAELIA applications on the studied watershed.

2. Modeling of hydrological processes in MAELIA platform

The MAELIA simulation model is implemented with GAMA (Taillandier et al., 2012), an open-source generic agent-based modeling and simulation platform. It provides an intuitive modeling language with high-level primitives to define agents and their environment. Its powerful Integrated Development Environment enables the non-computer modelers to manage huge GIS data and the interactions between complex environment and agents.

To represent water cycle in the platform, we used the formalisms of hydrologic cycles of the SWAT model, that were extracted from the theoretical documentation (Neitsch et al., 2009), Input/output documentation (Arnold et al., 2010) and the Fortran source code (http://swat.tamu.edu/software/swat-model/). In MAELIA, due to its specific objectives (e.g. to represent the effect of water shortage on irrigated crop yields and farm incomes), crop growth, domestic and industrial water uses and management of dams were represented through specific formalism.

For water management issues, the whole French territory is divided into elementary areas called Hydrographic Zones (ZH, Zones Hydrographiques) by the National Water and Aquatic Environments Agency of France (ONEMA). We used these ZH as sub-basins within both platforms MAELIA and SWAT. We used the French Landuse Identification System (RPG) to represent the agricultural plots. To simulate water balance and crop yield at field level, we re-implemented the Jeux d'O(Nolot and Debaeke, 2003). That Jeux d'O Model has been developed step by step according to results of agronomic experiments in the AGB during the last 20 years. It seeks to represent phenomena rather than mechanisms to ensure simplicity, robustness and accordingly large regional applicability. It represents effect of climate, soil and cropping system on yield for the eleven main crops of the AGB.

In the SWAT model, water balance is the driving force behind everything that happens in the watershed. Simulation of the hydrological cycle was separated into two major hydrological process classes: land phase and routing phase. The land phase controls the amount of water loading to the main channel in each (SWAT) sub-basin, while the routing phase can be defined as the movement of water through the channel network of the watershed to the outlet. SWAT is a semi-distributed hydrological model in which the hydrological balance is estimated and spatially allocated into so called "sub-watersheds". These latter are subdivided into Hydrologic Response Units (HRUs) representing a unique combination of land cover, soil type and slope. The subdivision into HRU is adapted to minimize the computational costs of simulations (Neitsch et al., 2009). A primary difference between SWAT and MAELIA is the way to represent processes into sub-basins and HRUs. SWAT simulates all the processes of the land-phase within HRUs (Hydrologic Response Units) loops, potentially spread over different sub-basins, and was then aggregated according to their spatial weight for each sub-basin. Therefore, SWAT model take not into account the geo-localized ponds, reserves or field plots. In MAELIA, to represent specific interactions within each sub-basin between its components (fields, pounds, water flow…), we introduced sub-basins loops including HRUs sub-loops for the modeling of land-phase. To deal with the specific hydrological behavior of the multiple combinations of crop-field determined by their soil, climate, crop management and water resource, we created a special type of HRU named HRU-RPG. Besides, the effects of elevation bands and snow are also simulated in the sub-basin iterations. Moreover, the water-use and the reservoirs releases in MAELIA are simulated through dedicated algorithms that represent the strategy of dam manager to respond to the demand of water-uses (mainly agriculture during the low-water period). The schematic of the MAELIA-hydrologic model structure is presented in Fig.1.

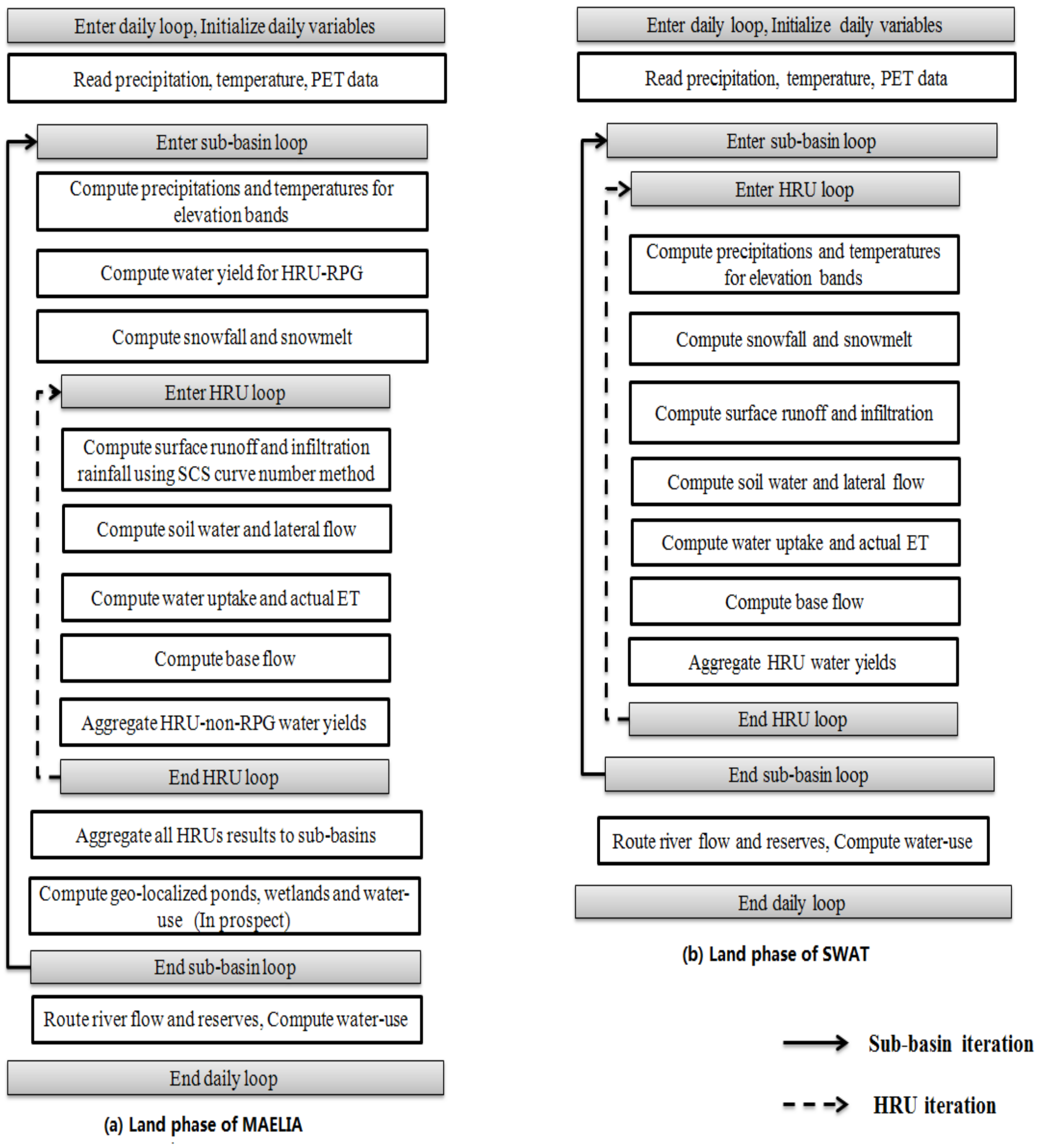


FIG.1Schematic flow chart showing the stream of processes simulating the water cycle of land phase in (a) MAELIA and (b) SWAT.

2.1, Sub-watershed and HRU discretization

In MAELIA platform, the non-field-plots parts of each ZH were partitioned into Hydrologic Response Units (HRUs). Besides, the HRUs-RPG were not the combinations of land-use/soil/slope, these were field-plots parts and directly simulated with the Jeux d'O Model (FIG. 2). The Jeux d'O Model receives inputs as the rainfall and the irrigation; it could calculate the evapotranspiration, surface runoff and the water that moves past the lowest depth of the soil profile for a field-plot. The outputs of Jeux d'O Model could be aggregated with the outputs of HRUs which were simulated with SWAT processes for a ZH. The surface areas of classic HRUs and HRUs-RPG are calculated as below:

$$SA_{ZH} = \Sigma\, SA_{HRU} + \Sigma SA_{HRU\text{-}RPG}$$

Where the SA_{ZH} is the surface area of the ZH (sub-basin), SA_{HRU} is the surface area of the classic HRU and the $SA_{HRU\text{-}RPG}$ is the surface area of the HRU-RPG.

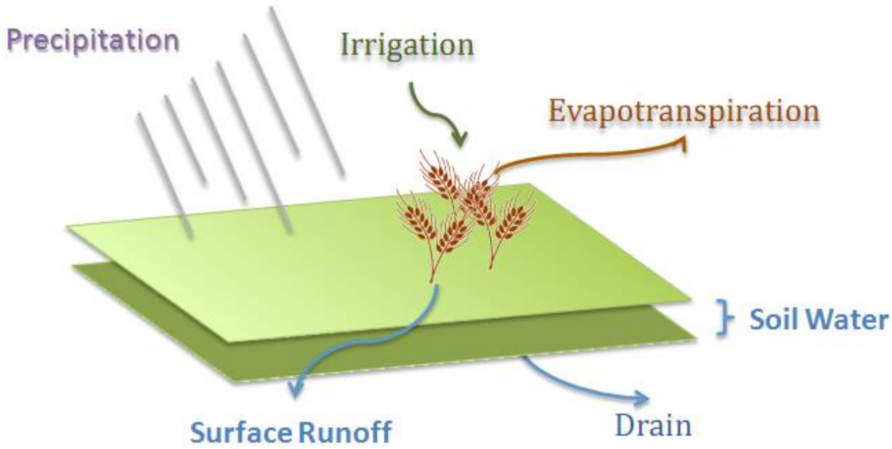


FIG. 2: Illustration of the water flow in Jeux d'O model.

2.2, Simulations of the land phase

The land phase of the hydrologic cycle is based on the following water balance equation:

$$SW_t = SW_0 + \sum_{t=1}^{t} (R_{day} - Q_{surf} - E_a - \omega_{seep} - Q_{lat})$$

Where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day I (mm H_2O), Q_{surf} is the amount of surface runoff on day I (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), ω_{seep} is the amount of percolation flow exiting the soil profile bottom on day I (mm H_2O), and Q_{lat} is the amount of lateral flow on day i (mm H_2O).

2.2.1, Elevation Bands and Snow

As the AGB is surrounded by medium and high mountains, snow melt during spring even summer is a key determinant of water flow. Our recent research about SWAT results sensitivity has revealed that the discretization of elevation bands and snow fall-melting calibration are key factors for SWAT-snow modeling (Sun et al., 2013). In respect that, precipitation and maximum and minimum temperatures are calculated for each band as a function of the respective lapse rate and the difference between the gage elevation and the average elevation for the band. For example:

$$R_{band} = R_{day} + (EL_{band} - EL_{gage}) \cdot \frac{plaps}{pcpdays \cdot 1000}$$

Where R_{band} is the precipitation falling in the elevation band (mm H_2O), R_{day} is the precipitation recorded at the gage (mm H_2O), EL_{band} is the mean elevation in the elevation band (m), EL_{gage} is the elevation at the recording gage (m), plaps is the precipitation lapse rate (mm H_2O/km), pcpdays is the average number of days of precipitation in the sub-basin in a year, and 1000 is a factor needed to convert meters to kilometers. In MAELIA, pcpdays is considered as a parameter.

Elevation bands that used in SWAT model are defined and specified by the users (average elevations, fractions), while MAELIA could calculate the fraction and the average elevation for each band in the sub-basin, as well as the intersections between bands and HRUs thanks to the capacities of GAMA platform (could manage interactions between GIS data and complex processes). That allows us to get a more accurate precipitation/temperature simulation for each elevation band, and also enables us to simulate the snow-fall, snow-melt, snow-cover and snow-sublimation in the sub-basin loops instead of HRUs iterations. Moreover, we could define an elevation (Elevation_for_snow) that once the top altitude of a sub-basin is less than it, the calculation of the elevation bands and snow-effects in this sub-basin could be avoid.

2.2.2, Surface runoff

We used the SCS Curve Number method for the surface runoff simulations. The SCS runoff equation is an empirical model that came into common use in the 1950s. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$$

Where Q_{surf} is the accumulated runoff or rainfall excess (mm H_2O), R_{day} is the rainfall depth for the day (mm H_2O), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), and S is the retention parameter (mm H_2O). In MAELIA, we use the soil moisture method for the calculation of daily CN value, where the retention parameter S is varied with soil profile water content. Meanwhile, the overland flow and the effects of vertisols are not included compared with the SWAT model.

2.2.3, Soil water and lateral flow

Water that enters the soil may move along several different pathways. The water may be removed from the soil by plant uptake or evaporation. It can percolate past the bottom of the soil profile and ultimately become aquifer recharge as the base flow. A final option is that water may move laterally in the profile and contribute to river flow. In MAELIA model, percolations and lateral flows were calculated for each soil layer in the profile, water is allowed to percolate or become lateral flow when the water content exceeds the field capacity water content. The same as SWAT, MAELIA incorporates a kinematic storage model for subsurface flow.

$$Q_{lat} = 0.024 \cdot \left(\frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}}\right)$$

Where Q_{lat} is the water discharge from layer outlet (mm H_2O), $SW_{ly,excess}$is the quantity of water that exceeds the field capacity for a layer (mm H_2O), K_{sat} is the saturated hydraulic conductivity (mm/h), slp is the average slope of the sub-basin (m/m), Φ_d is the drainable porosity of the soil layer (mm/mm) and the L_{hill} is slope length for lateral flow (m). For reason of simplification, perched water table, bypass flow and soil temperature are not simulated in MAELIA platform.

2.2.4, Water uptake and actual Evapotranspiration

Evapotranspiration includes evaporation from the soil, transpiration and sublimation. An accurate estimation of evapotranspiration is critical in the assessment of water resources.

In MAELIA, the Potential Evapotranspiration (PET) is provided in a 8 x 8km grid computed by the climatic model SAFRAN (Page, 2008) that extrapolates weather station measures. Instead of using one single PET for all over the watershed, the PET data of MAELIA were generated with a computer method that each sub-basin (ZH) has a specific value for every day. As we had used the SCS Curve Number method for calculating surface runoff, the canopy storage was considered as 0. The actual amounts of sublimation, evaporation from the soil and plant uptakes were then calculated one after another.

2.2.5, Groundwater and base flow

The difference between groundwater and soil profile water is that the groundwater is under pressure greater than atmospheric while the soil profile water is at a negative pressure. The groundwater is recharged by infiltration/percolation while it will discharge into rivers as base flow, or move upward from the water table into the capillary fringe as "revap", or even percolate into the deep aquifer which was considered as a lost portion in the model. MAELIA simulates only unconfined shallow aquifers in each sub-basin.

2.3, Simulation of the routing phase

MAELIA models only channelized water flow in the watershed. We used Manning's equation to define the rate and velocity of flow, water is routed through the channel network using the Muskingum River routing method. The water balance equation for a river reach of sub-basin is:

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - tloss - E_{ch} + div + V_{bnk}$$

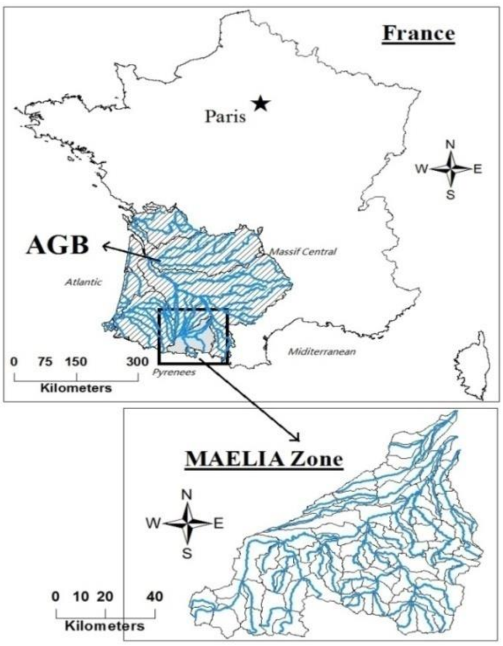
Where $V_{sotred,2}$ is the volume of water in the reach at the end of a day (m^3 H_2O), Vstored,1 is the volume of water in the reach at the beginning of a day (m^3 H_2O), Vin is the volume of water flowing into the reach (m^3 H_2O), Vout is the volume of water flowing out of the reach (m^3 H_2O), tloss is the volume of water lost from the reach via transmission through the bed (m^3 H_2O), Ech is the evaporation from the reach (m^3 H_2O), div is the volume of water added or removed from the reach (m^3 H_2O), and Vbnk is the volume of water added to the reach via return flow from bank storage(m^3 H_2O). A detailed discussion of the Muskingum method and water routing can be found in SWAT theoretical documentation (Neitsch et al., 2009).

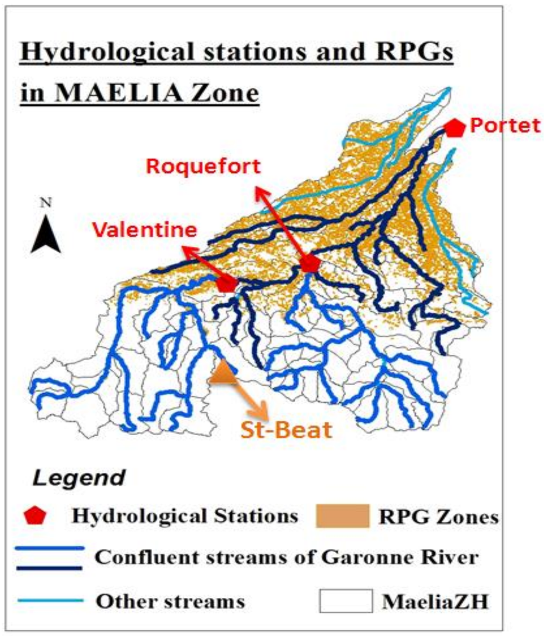
3. Case Study

A main objective of the MAELIA platform is to develop a computer tool for governing the water scarcity in the Adour-Garonne Basin (AGB).The AGB represents one fifth of the land area of France (11600 km2), it is located in the south-west of France. Water scarcity is a structural problem in the AGB, with an average annual deficit between demands and resources of 250 million m^3. In this basin, irrigated agriculture is the main consumer of water (about 80%) during the low-water period.

The Garonne watershed is the most important sub-basin in the AGB with a drainage area of 49700 km^2 while the Garonne River is the main river in the AGB which length is about 525 km (Sauvage et al., 2003). For testing the feasibility and the performance of MAELIA platform in a first time, the model were applied at the upper part of Garonne watershed, called hereafter MAELIA Zone (FIG. 3a). The drainage area of the MAELIA Zone is over 6000 km^2, length of the Garonne River in this area is about 140 km. As a part of Garonne watershed (upstream of St-Beat) is located in Spain (about 500 km^2), we don’t have enough data to model it, the recorded values of discharge at the site St-Beat are therefore used as a point-source at a first time.

Simulations are performed for a period of 1999-2009, using the predefined parameters which have been calibrated by a ArcSWAT application. The differences of water-flow simulations between MAELIA and SWAT are then evaluated by comparing the simulated flow rate of SWAT and MAELIA at three selected measuring sites (FIG. 3b), the coefficient of determination (R^2) has also been calculated. Where the Valentine and Roquefort stations are the outlets of southwestern and southeastern parts of the Garonne River in MAELIA Zone, while the Portet station is the general outlet of the studying watershed. The arable zone including irrigated crops is mainly located in the northern parts of the MAELIA Zone.



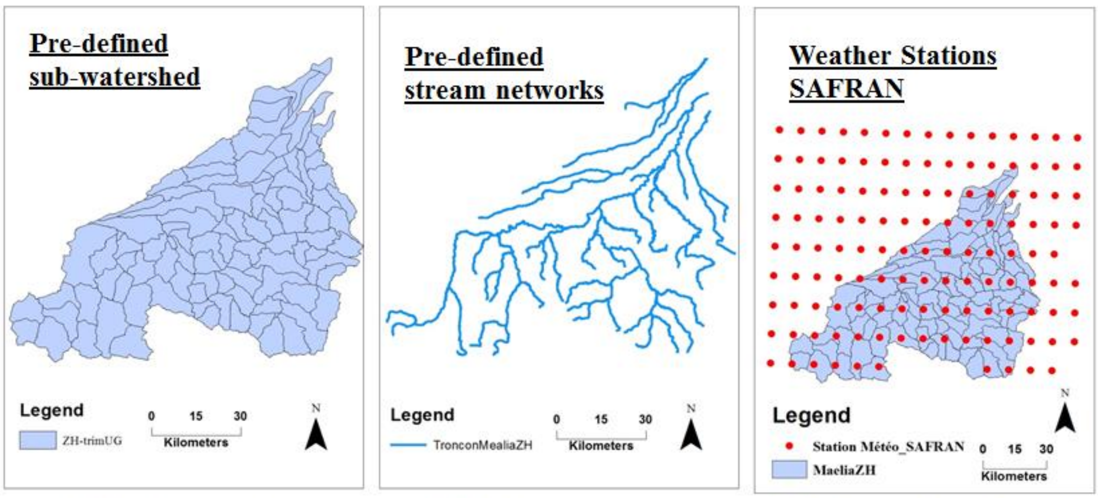


(a) AGB in France and MAELIA Zone (b) Hydrological stations, St-Beat and RPGs.

FIG. 3: a) The Adour-Garonne Basin (AGB) in France and the MAELIA Zone (Upper part of the Garonne Watershed). b) Selected hydrological stations, "point-source" St-Beat and distribution of RPG areas in MAELIA zone.

3.1, Description of the Input Data

A Digital Elevation Model (DEM) with 50 meters resolution was prepared by the National Geographical Institute of France (IGN), the topography of this testing watershed ranges from a broad, flat alluvial valley (northern parts) to steep, rugged mountain slopes (southern parts), with a range in elevation from 130 to 3173m. Soil data was obtained from the database of the National Institute of the Agronomic Research (INRA). In total, the soil map contains 22 Soil Mapping Units (SMU) with 75 different Soil Types Units (STU) for the MAELIA zone. Each STU is described by all the needed parameters estimated through observations and pseudo-transfer functions (e.g. soil layers, depth, saturated conductivities etc.). The land cover map of Corine-Land-Cover France (CLC) was simplified to delineate 4 types of land-use, forest, water, urban areas and agricultural areas. Climatic information comes from the SAFRAN model (see above). 104 pre-defined ZHs (sub-basins) are necessary to cover the MAELIA zone. All the monitoring data of the Garonne River (river networks, discharges etc.) were supplied by the Water Agency of Adour-Garonne (AEAG). The hydrologic network data in MAELIA Zone contains numerous and complicated rivers, streams, canals and groundwater pathways connecting with different hydrological nodes. For the purpose of the comparison between SWAT and MAELIA results about water cycle in the watershed, we have traced the main channels from the original data with a computer method, that each ZH comprised a single main river reach with an inlet and an outlet (Headwater ZH only had outlets). The pre-defined sub-watershed and stream networks as well as the data SAFRAN are illustrated in FIG. 4:



a) Pre-defined sub-watershed (ZH) b) Pre-defined stream networks c) Weather stations SAFRAN

FIG.4 Illustrations of a) pre-defined sub-watershed (ZH); b) pre-defined stream networks; c) Weather stations in SAFRAN database.

3.2, Sensitivity analysis

3.2.1, Morris Method

A sensitivity analysis is conducted for the MAELIA application to identify the important factors of our new GAMA-based model. Due to the large number of parameters that we have to test, the Morris method (Campolongo et al., 2007; Morris, 1991) is used in the study. It is based on a "One-factor-At-a-Time" (OAT) design of experiments, and is generally used when the number of model parameters is large enough to require computationally expensive simulations. For each parameter, two sensitivity estimates are obtained, both based on the calculation of incremental ratios at various points in the input space of parameters. The incremental ratio is the ratio between the variation of the model output in two different points of the input space (where only one parameter is varied at a time) and the amplitude of the variation of the parameter itself. The Morris method calculates elementary effects (Ri) due to each input factor using the following equation:

$$R_i(x_1. \ldots .x_n.\Delta) = \frac{y(x_1. \ldots .x_{i-1}.x_i + \Delta.x_{i+1}. \ldots .x_n) - y(x_1. \ldots .x_{i-1}.x_i.x_{i+1}. \ldots .x_n)}{\Delta}$$

where y(X) is the output. X = (x1.x2. ….xn) is the n-dimensional vector of factors being studied. Δ is the elementary increment of the OAT.

The method samples values of X from the parameter space to calculate mean (μ, assessing the overall influence of the factor on y(X)) and standard deviation (σ, estimating the totality of the higher order effects, i.e. nonlinearity or interactions with other factors) of all the Ri obtained for each factor. In our case, the exploration of the parameter space was improved by the use of a Latin Hypercube Sampling (LHS), as already illustrated, for example, in (Francos et al., 2003; Van Griensven et al., 2002). Around each point of the LHS of dimension t, an OAT is achieved, so the total number of model evaluations needed is t(n+1). The first sensitivity estimate (μ) is obtained by computing a number of incremental ratios at different points of the input space, and then taking the average of their values. Whereas, the second measure (σ) is the standard deviation of their values, and is useful to detect parameters either interacting with other parameters, or the effect of which is non-linear (Saltelli et al., 2004). A large measure of central tendency μ indicates an input with an important overall influence on the output (total effect), while a large σ indicates either a parameter with non-linear effect on the output, or a parameter involved in interaction with other parameters (higher than one-order effects). The most relevant parameters are those located in the top right area of the σ (spread) versus μ (strength) plot, where both sensitivity measures are high.

3.2.2, Sensitivity analysis for MAELIA application

In our case, the sensitivity of stream flow to MAELIA is indexed for over 41 parameters (Table 1), with 33 belongs to the hydrologic sub-model (SWAT), and 8 belongs to the farmer agents sub-model (Jeux d'O). We choose 12 hydrological sites as the LHS, the number of simulations (504, for 12 local OAT of 42 simulations) is in accordance with literature which suggest at least five OAT for robustness (Confalonieri et al., 2010). A Uniform distribution is applied as which is commonly used in SWAT literatures (e.g. (Cibin et al., 2010; Moreau et al., 2013; Muleta and Nicklow, 2005)), however, it is a highly-general-used method when the main objective is to understand model behavior (Monod et al., 2006). Simulations are performed over seven years (2000-2006) with 2 years warm-up period (2000-2001), then indices (i.e. μ* which is mean of absolute elementary effects Ri and σ) are calculated using the 'sensitivity' R package.

Table 1, MAELIA parameters used in the sensitivity analysis

Parameter	Min value	Max value	Unit	Descriptions
SURLAG	0	10	day	Surface runoff lag time
CH_N	0	0.1	-	Manning coefficient valuefor tributary channels
ESCO	0.01	1	-	Soil evaporation compensation factor
EPCO	0	1	-	Plant uptake compensation factor
GW_DELAY	0	50	day	Groundwater delay time
GW_REVAP	0.001	0.2	-	Groundwater *revap* coefficient
RCHRG_DP	0	1	-	Aquifer percolation coefficient
ALPHA_BF	0	0.3	-	Baseflow recession constant
REVAPMN	0	3000	mm	Threshold water level in shallow aquifer for revap
GWQMN	0	1500	mm	Threshold water level in shallow aquifer for baseflow
CN_2	-10 %	+10 %	-	SCS Curve number (one value per landuse: AGRL: 75; FRST: 70; URBN: 65; WATR: 92)
OV_N	0.01	0.3	-	Manning coefficient value for overland flow.
msk1	0.5	1	-	Muskingum coefficient msk2 = 1 – msk1
msk2	0	0.5	-	
SHALLST	0	2000	mm	Initialisation of shallow aquifers.
RCHST	0	10 000	m^3	Initial water volume of channels.
mskX	0	0.5	-	Muskingum wedge factor
μ	0.0015	0.0045	m^3/m^3	Shallow aquifer yield
LAI	0.5	3	m^2/m^2	Leaf Area Index.

SWinit	0	1	-	Initial soil moisture (fraction of field capacity)
tlaps	-4.0	-8.0	K/km	Temperature change with altitude
plaps	200	800	mm/km/y	Precipitations change with altitude
snocovmx	50	300	mm	Snow water equivalent corresponding to full snow cover
sno50cov	0.1	0.5	-	Snow water equivalent corresponding to half snow cover
timp	0.2	0.8	-	Snow pack temperature lag factor
sftmp	0.01	2	°C	Snow fall min temperature
smtmp	0.01	2	°C	Snow melt temperature
smfmn	0.5	3	mm/ °C /day	Minimum snow melt rate (21 décembre)
smfmax	6	10	mm/ °C /day	Maximum snow melt rate(21 juin)
pcpdays	140	180	-	Average number of rainy days per year
Elevation_for_snow	500	2500	m	Elevation threshold above witch snow is considered. (500; 1000; 1500; 2500)
travail_jour	10	14	h/day	Average number of working hours per day
uth_par_hectare	90	250	UTH/ha	Yearly working hours per ha
hauteurPluieMaxIrrigation	10	30	mm	Max. precipitations level allowed for continuing irrigation.
hauteurPluieMaxSemi	10	30	mm	Max. precipitations level allowed for sowing
hauteurPluieMaxRecolte	10	30	mm	Max. precipitations level allowed for harvesting
SurfaceIrriguee	1	2	ha/day	Irrigable surface per days
dureeTourEau	5	10	day	Lag return of irrigation. It is an integer.
rendement_malus	10	30	%	Yield loss if harvesting cannot happen on the due period

4. Results and discussions

4.1, Stream flow simulation and Comparisons between SWAT/MAELIA

Stream flow hydrographs at the three different sites are presented in Figs. 5, 6 and 7 showing the predictions (2000 - 2009) of flow rate of the both two models (SWAT and MAELIA). Since the results of the two models are quite similar and the range of the flow rate is highly wide (0 – 2000 m^3/s), we use a logarithmic scale with the base of 10 for displaying the daily flow. The values of coefficient of determination (R^2) are marked in the graphics as well.

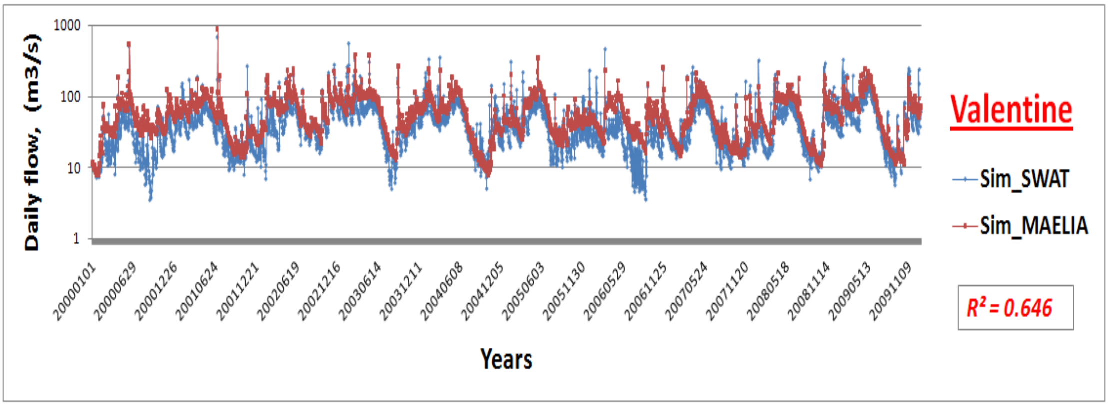


FIG.5 Daily stream flow for the period 2000-2009 at Valentine, displayed with Log_{10}.

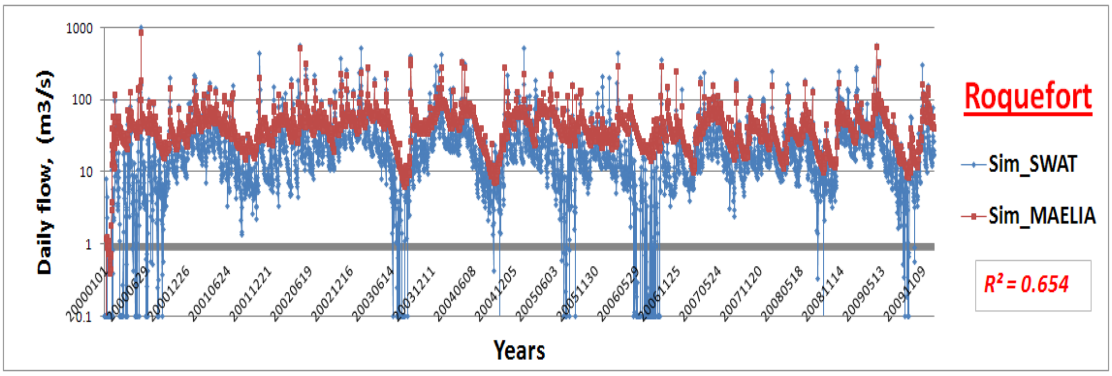


FIG.6 Daily stream flow for the period 2000-2009 at Roquefort, displayed with Log_{10}.

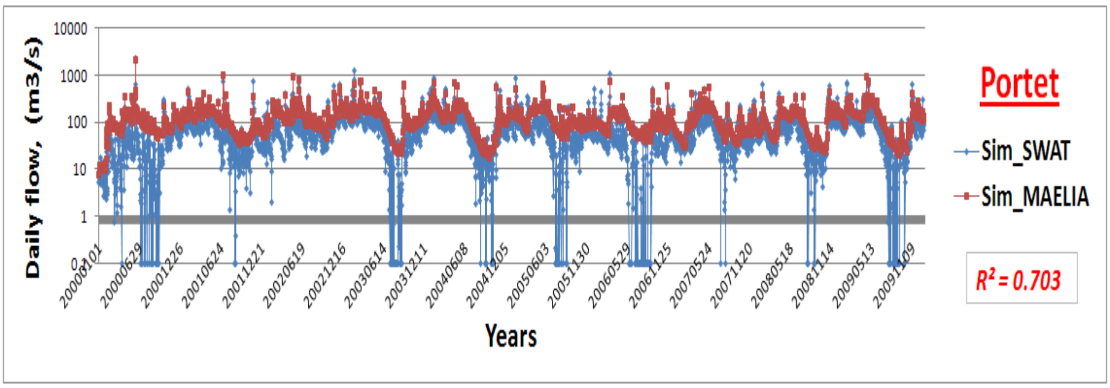


FIG.7 Daily stream flow for the period 2000-2009 at Portet, displayed with Log_{10}.

Generally, we are glad to see that the MAELIA platform functions with the hydrological module which is based on SWAT model. Meanwhile, we could easily find that SWAT simulate less water than MAELIA during the low-water period (July - October). At the Roquefort and Portet stations, SWAT predict a discharge barely at 0 during July and October; as for the Valentine station, since it is located just at the downstream of the "Point-Source" St-Beat, which supplies an average discharge at about 20 m^3/s during the low-water period, the simulations of SWAT are much higher. That is generally because of the different plant-growth processes that we used in the two models. In SWAT, the growth of forests and agriculture plants and the evolution of their Leaf Area Index (LAI) are simulated using Heat-Unit method. As in MAELIA, we use Jeux d'O model for simulating the growth of crops, in which the variations of LAI are not calculated, while for the forest and other plants (grass, etc…), the LAI is dealt as a parameter. With all the other SWAT-calibrated parameters, the value of LAI in MAELIA is fixed to 2 for a comparison. As the LAI in SWAT is always probably up to 3 in the summer for all types of plant, the SWAT model will simulate more transpiration and less stream water during the low-water period. Moreover, the processes of the water-use restrictions and water-management in MAELIA will increase these discrepancies especially during the low-water period.

The results at the Roquefort station (Fig. 7) - where its upper parts are generally located in the mountainous areas – shows the simulation of SWAT is always under MAELIA. This phenomenon is mainly due to the different methods that we used for simulating the precipitations of elevation bands and the snow effects. Since SWAT use a series of pre-specified elevation bands, MAELIA calculate the proportions and the average elevations of each band. Even more, the climate data of MAELIA is provided by SAFRAN in 8x8 km grid, which the elevations of the climate stations are considered as the center of each grid. That will cause the different predictions of rainfall and snowfall for the elevation bands, partially at the mountainous areas.

At the same time, the results shows that the simulations of daily flows of MAELIA and SWAT are most similar at the Portet station amongst the three selected stations, with the greatest values of coefficient of determination ($R^2 = 0.703$). As the RPG areas are mainly dispread in the northern part of MAELIA zone, at the downstream of the Valentine and Roquefort stations; we could say that although the equations and formalisms used in Jeux d'O model of MAELIA simulate plant growth not the same as SWAT does, the predictions of the cropland water-yield are roughly alike between SWAT and MAELIA.

4.2, Parameter Sensitivity of MAELIA

Since MAELIA use a series of different processes programming in a different language (GAMA) compared with SWAT, the sensitivity analysis of SWAT parameters could not be done in the same way. However, one of the objective is to identify the important factors of MAELIA model, we decide to perform the Moris Method only on MAELIA model, the common regulars of these MAELIA-parameters will be then recognized and compared with SWAT literatures. Based on sensitivity results of flows at 12 site levels, we could build a complete list of parameters that are considered influent enough (e.g. at least 10% of the maximum μ^* or σ). We would get the following list in Table 2.

Table 2. List of parameters considered as influent on water flows

Parameter	Number of occurrence below the 10% threshold	
CN2_AGRL	85	(89%)
Elevation_for_Snow	78	(81%)
CN2_FRST	75	(78%)
LAI	59	(61%)
OV_N	48	(50%)
SURLAG	48	(50%)
Plaps	45	(47%)
Tlaps	44	(46%)
Sftmp	31	(32%)
Smfmax	28	(29%)
CH_N	19	(20%)
REVAPMN	16	(17%)
RCHRG_DP	13	(14%)
Smfmn	12	(13%)
GW_DELAY	11	(11%)
Pcpdays	11	(11%)
SHALLST	11	(11%)
msk1/ msk2	9	(9%)
CN2_WATR	8	(8%)
ESCO	2	(2%)

Nowadays, many publications on SWAT model applications are available, while a few of them had provided detailed information on sensitivity analysis, 11 parameters of SWAT had been identified and widely used as the "sensitive" parameters for water flow calibration. It include: ALPHA_BF, CN2, ESCO, GW_DELAY, GW_REVAP, GWQMN, OV_N, SFTMP, SOL_AWC, SOL_K, SURLAG (e.g. Arnold et al., 2000; Cibin et al., 2010; Francos et al., 2003; van Griensven et al., 2006; Muleta and Nicklow, 2005; White and Chaubey, 2005).

Twenty "sensitive" MAELIA parameters to the water flows are listed in table 2. We could unsurprisingly find that the processes concerned surface runoff are most sensitive to water flows, in which CN_2 determines the amount of runoff while OV_N and SURLAG determines the time of concentration. Meanwhile, the second order of the most sensitive parameters concerned with the elevations bands (plaps, tlaps) and snow effects (sftmp, smtmp, smfmax), and third order of the most sensitive parameters seems to link with the groundwater processes (REVAP_MN, RCHAG_DP, ALPHA_BF, SHALLST).

Otherwise, the three novel parameters in MAELIA "Elevation_for_Snow", "LAI" and "pcpdays" are proved to be sensitive, it is quite logical as "Elevation_for_Snow" activates or deactivates the calculations of snow processes, "LAI" influence the amount of transpiration so as well the soil properties, and the "pcpdays" has an effect on the simulations of rainfall at elevation bands.

As for the soil properties and groundwater, the parameters Base-flow recession constant (ALPHA_BF), Threshold water level in shallow aquifer for base-flow (GWQMN) and Soil evaporation compensation factor (ESCO) were often shown to be very influential in some studies (e.g. van Griensven et al., 2006; Guse et al., 2013), but it is not like that in our study. Meanwhile, the threshold water level in shallow aquifer for "revap" (REVAPMN) seems to be important in MAELIA. The reasons could be that: i) MAELIA specified the values for some soil characters such as SOL_AWC, SOL_K estimating through observations and pseudo-transfer functions, the ESCO could be less significant with fixed soil-parameters. ii) Since the growths of plants are not simulated in MAELIA, the parameters ESCO and EPCO might be less important with fixed LAI. iii) As the base-flow supplies stream flows mainly during the low-water period, while the agent-based water restrictions and management processes in MAELIA could ensure a minimum amount of stream water at this time, that would lighten the significance of the base-flow effects as well as the sensitivities of its concerning parameters.

5, Summary and Recommendation

The hydrological formalisms and equations of SWAT are analyzed and re-implemented within MAELIA platform. For modeling purposes in MAELIA, a watershed has been partitioned into a number of pre-defined sub-basins, which are named Zones Hydrographiques (ZH) in France that are defined by the National Water and Aquatic Environments Agency of France (ONEMA). Simulation of the hydrology of a watershed is separated into two major divisions – land phase and routing phase. The land phase of the hydrologic cycle controls the amount of water loadings to the main channel in each ZH while the routing phase simulate the movement of water through the channel network of the watershed to the outlet. Within land phase, the water cycle of croplands is simulated at a field level using Jeux d'O model, while the hydrologic cycle of the non-agriculture land is calculated with SWAT processes. The non-agriculture lands are then subdivided into Hydrologic Response Units (HRUs) representing a unique combination of land cover, soil type and slope. The hydrologic module of MAELIA allow simulation of elevations bands, snow effects, croplands water, surface runoff, soil water, actual evapotranspiration, base flow and channel routing at daily interval. However, some of the SWAT-processes have been changed in MAELIA for different objectives.

Theoretically, MAELIA simulate a more accurate precipitations and temperatures for the elevation bands with the calculated values of average elevations and proportions for each bands rather than user-specified ones. It will be worth to verify this supposition with the measured data. As well, it perhaps will be interesting to add these formalisms in the ArcGIS interface for further Arc-SWAT applications.

Since MAELIA don't simulate plant growths for the non-agriculture lands for reducing the computational time, the Leaf Area Index (LAI) becomes an important parameter

(Tab. 2) that influence greatly the transpiration processes as well the soil properties. It will be worthy of discussing its impacts and the probable improvements (using different LAI values for different types of Land-use, trying some other simple formalisms for expressing the variations of LAI, etc…).

Representing some of the land-phase processes in sub-basin loops may be a drawback in the computational time scale, compared with that all the land-phase processes in HRU loops. However, we could introduce the geo-localized field plots with this modification; even more, detailed ponds and reserves might can be integrated according to their different characters (e.g. connectivity with river network, position in the watershed, volume).

Besides, SWAT model use a single value of Potential EvapoTranspiration (PET) for the entire watershed, while the PET values in MAELIA are generated for every sub-basin using interpolation method. Meanwhile, overland flow, vertisols, perched water table, soil temperature and deep aquifers are not simulated in MAELIA on purpose of simplification. It perhaps will be the worthwhile studies for testing the effects of these phenomena.

A sensitivity analysis outlined in this study (Tab. 2) showed that the three novel parameters in MAELIA "Elevation_for_Snow", "LAI" and "pcpdays" are influential, which are related to elevation-bands definition and transpiration. Meanwhile, the parameters connecting with soil properties and base-flow (ESCO, ALPHA_BF) become less important. The determinations of the values of some soil parameters (AWC, SOL_K, etc.), the changes in calculating plant growths (Jeux d'O) and the introductions of agent-based water management processes in MAELIA are the mainly cause of these circumstances.

The hydrologic module of MAELIA is intended for simulating the water cycle in a watershed which could be interacted with the other modules such as agriculture module, normative module and agent-based management module within the entire platform. Due to the lack of calibration and validation results of the whole platform, the comparison of the performances of SWAT and MAELIA could not be analyzed yet. Equally, some of the hypothesis that we proposed in this paper (effects of elevation bands processes, plant growths processes, etc…) need to be checked in the further works.

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