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Integrating operational watershed and coastal models for the Iberian Coast: Watershed model implementation – A first approach

David Brito, F.J. Campuzano*, J. Sobrinho, R. Fernandes, R. Neves

Maretec – Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

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A B S T R A C T

River discharges and loads are essential inputs to coastal seas, and thus for coastal seas modelling, and their properties are the result of all activities and policies carried inland. For these reasons main rivers were object of intense monitoring programs having been generated some important amount of historical data. Due to the decline in the Portuguese hydrometric network and in order to quantify and forecast surface water streamflow and nutrients to coastal areas, the MOHID Land model was applied to the Western Iberia Region with a 2 km horizontal resolution and to the Iberian Peninsula with 10 km horizontal resolution. The domains were populated with land use and soil properties and forced with existing meteorological models. This approach also permits to understand how the flows and loads are generated and to forecast their values which are of utmost importance to perform coastal ocean and estuarine forecasts. The final purpose of the implementation is to obtain fresh water quantity and quality that could be used to support management decisions in the watershed, reservoirs and also to estuaries and coastal areas.

A process oriented model as MOHID Land is essential to perform this type of simulations, as the model is independent of the number of river catchments. In this work, the Mohid Land model equations and parameterisations were described and an innovative methodology for watershed modelling is presented and validated for a large international river, the Tagus River, and the largest national river of Portugal, the Mondego River. Precipitation, streamflow and nutrients modelling results for these two rivers were compared with observations near their coastal outlet in order to evaluate the model capacity to represent the main watershed trends. Finally, an annual budget of fresh water and nutrient transported by the main twenty five rivers discharging in the Portuguese coast is presented.

1. Introduction

In recent decades, the population increase in urban areas led to a spatial concentration of water demand for production and irrigation. This demand was generally compensated by using surface water, which in the Iberian Peninsula present a high inter-annual variation, constraining water management decisions. In addition, population concentration in alluvial plain areas increased the need of appropriate flood risk policies and action plans in order to prevent and mitigate flooding episodes.

In order to obtain the appropriate information for water resources planning and management, river monitoring networks were designed and implemented. The hydrometric network in Portugal was observing streamflow and precipitation until the 90's or 00's while water quality monitoring started in the 00's. Due to economic constraints, the amount of active stations and the data reliability from the Portuguese hydro-meteorological network has been declining as a result of the maintenance interruption of the automatic monitoring stations since the beginning of the 2010's and field data collection in Portugal is nowadays quite sparse. The Portuguese case is part of a more general trend in hydrometric networks decline observed in many countries around the world (Mishra and Coulibaly, 2009).

A way to reduce the uncertainty of the quality and quantity of the fresh water resources is through mathematical models. Numerical models, once validated, could fill data gaps and link sources of pressure to the observed state in the catchment and allow scenario testing. Watershed models first appeared in the 50's – 60′s making the focus on water - the called rainfall-runoff modelling – (Donigian and Imhoff, 2002), and not until the 70′s did water

* Corresponding author.
E-mail address: campuzanofj.maretec@tecnico.ulisboa.pt (F.J. Campuzano).

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quality begin to gain notice, with models focusing in the soil loss and nutrient and pesticide export to rivers (Horn et al., 2004).

In the next decades the need for management-oriented process integration led to the development of watershed models with detailed land management such as the SWAT model (Neitsch et al., 2005) which is a semi-distributed watershed model with a strong semi-empirical component that reduces running time over large basins, but strongly increases the need for field data prior to model implementation.

In last decade, distributed physically-based models developed with the increasing computation capacity reducing the number of model empirical parameters and thus increasing model applicability in systems lacking data. Two examples are the MIKE SHE model (Refsgaard and Storm, 1995) and the SHETRAN model (Ewen et al., 2000) which were both originated from the SHE model (*Système Hydrologique Européen*) and are a reference in the generation of physically-based, integrated, distributed watershed models. Conceptually, these models and MOHID (Neves, 2013) are very close; nevertheless the former use finite-differences as the numerical method while MOHID Land uses finite-elements and the equations are solved for volumes ensuring, by default, mass conservation.

In this work, we present the tools, methodologies and a preliminary validation as the base to obtain accurate forecasts of fresh water quantity and quality that could be used to support modellers and managers targeting large regions at different scales, such as watersheds, reservoirs, estuaries, and coastal areas.

2. Study area

The study area covers the entire Iberian Peninsula with a surface area around 580 000 km^2 and more specifically to the rivers discharging in the Portuguese coastal area. Iberia presents several largest rivers including the Douro River (area ca. 100 000 km^2), the Tagus and the Ebro rivers (area ca. 80 000 km^2), the Guadiana River (area ca. 70 000 km^2) and the Guadalquivir River (area ca. 60 000 km^2) that, with the exception of the Ebro River, have international character sharing their catchment between continental Spain and Portugal and discharging on the Atlantic Ocean draining on its way almost two thirds of the territory. For the scope of the validation of the presented methodology study, we will focus mainly on the Tagus River with a total length ca. 1000 km, the longest river of the Iberian Peninsula, and the Mondego River, the longest river located exclusively in Portuguese territory (Length 230 km, area 6.600 km^2).

The determination of the rainfall is of the utmost importance, as it is a primary variable in most hydrological models. The precipitation in the Iberian Peninsula is characterized by high spatial and temporal variability because of a complex orography and diverse atmospheric regimes. Mean annual precipitation varies between more than 2000 mm in the northwest coast and less than 200 mm in the south-eastern coast (AEMET and IM, 2011).

In Iberia most of the precipitation falls between October and May and is produced by large-scale atmospheric perturbations that originate in the Atlantic sector and move eastwards (Serrano et al., 1999; Santos et al., 2005). During winter, western Iberia is affected by westerly winds, influenced by the position of the Icelandic low, that carry moist air and produce rainfall events mainly in northern Portugal. The precipitation is intensified by the passage of cold fronts associated with families of transient depressions and more efficient when the Icelandic low is very deep and shifter southwards (Trigo et al., 2004). In addition to the seasonal character, the Iberian Peninsula is also characterized by a strong inter-annual precipitation variability presenting very wet and dry years occur with some frequency affecting the hydrological cycle and by consequence the river flow and water resources (Trigo et al., 2004; Paredes et al., 2006).

3. Materials and methods

3.1. Modelling grids

Two domains covering the Iberian Peninsula (IP domain) and the Western Iberia (WI domain), with 10 km and 2 km horizontal resolution respectively (Fig. 1), were populated using the NASA SRTM three arc-second digital terrain elevation, that in the studied area has a horizontal resolution of 70–90 m (Farr et al., 2007). The IP domain, with 80 × 130 cells in horizontal and 8 vertical layers, allows the reproduction of large trans-boundary rivers discharging in Western Iberia as the Tagus, Douro and Guadiana rivers at their natural state. The WI domain, 250 × 160 cells in horizontal and 8 vertical layers, provides high resolution results for Portugal and the Galicia region (Northwest Spain), encompassing watersheds up to 10 000 km^2.

Along with the topographic data, the model was provided with land use and soil properties. In order to have a common source for both modelling domains, the Corine Land Cover 2006 – CLC2006 (EEA, 2007) with a resolution of 100 m was used to derive crop types for the vegetation growth model, surface impermeabilisation and Manning resistance following Van der Sande et al. (2003) and Chow (1959) suggested correspondences.

The soil hydraulic permeability and retention capacity control the infiltration and groundwater movement and surface water quantity. Soil map distribution and hydraulic characteristics, necessary to specify the van Genuchten model parameters, were obtained from the Joint Research Centre database (http://eusoils.jrc.ec.europa.eu/) for both domains with a 900 m resolution.

In the absence of detailed information on agricultural practices in a wide area as the Iberia Peninsula, it was used the auto-fertilization concept from SWAT model. In practical terms, this means that agricultural practices are assumed to be optimal since the fertilization occurs according to the plant needs. Maximum values of 50 kg/ha.day and 200 kg/ha.year of fertilizer where considered based on the good agricultural practices guide for Portugal (DGADR, 1997).

The objective of this model implementation was to represent the large scale hydrological and water quality processes, including evapotranspiration and river discharges, and not the local processes associated for example with land use changes smaller than the cell size. More detailed approaches can however be implemented in areas of interest having the boundary conditions given by the Iberia Peninsula or Western Iberia model applications.

The atmospheric boundary conditions for the WI domain were obtained from the MM5 model (Grell et al., 1994) with a horizontal resolution of 9 km implemented by the IST meteorological group (http://meteo.ist.utl.pt). For the IP domain, results from a WRF model (Skamarock et al., 2005) application with 12 km resolution computed by Meteogalicia (http://www.meteogalicia.es) were used as atmospheric forcing. Both meteorological models results were interpolated to the MOHID Land grids.

3.2. MOHID land model

The MOHID Land model is the catchment component of the MOHID Modelling System (Neves, 2013; http://www.mohid.com). The MOHID land model is a 3D distributed, continuous, physically based, variable time step model using a finite-volume approach based on mass and momentum balance equations. The simulated processes include interception and evaporation in leafs, infiltration and evapotranspiration in soil/vegetation, vegetation growth,

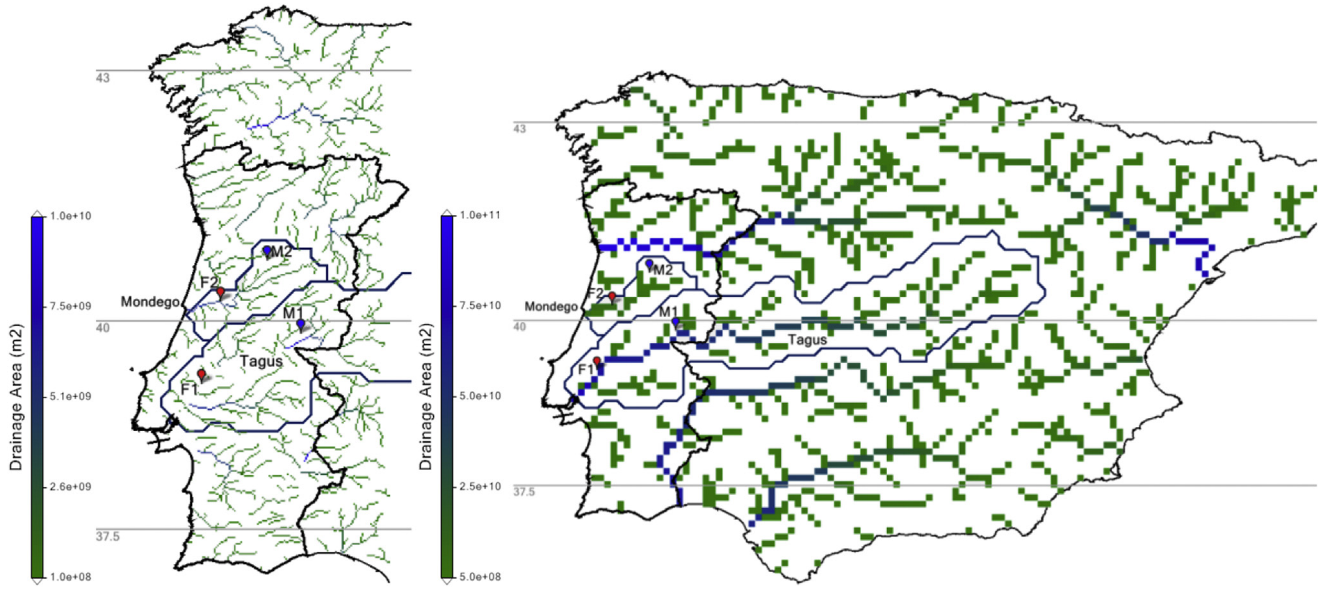

Fig. 1. Main water lines in the Western Iberian Peninsula (WI domain, left) and in the complete Iberian Peninsula (IP domain, right) indicating the drainage area obtained with the MOHID Land for the 2 and 10 km resolutions respectively and the location of the hydrological (F1 and F2) and meteorological (M1 and M2) stations used for the model validation. The drained area by the Mondego River and the Tagus River appears enclosed by continuous lines in both domains.

routing of water trough surface runoff, porous media or river network and water quality processes, i.e. mineralization, nitrification, denitrification in porous media and rivers, including primary production (Trancoso et al., 2009). Sediment transport and erosion/deposition are also computed for surface waters. The main innovation for this application was the simultaneous simulation of all watersheds without the need of identifying catchment limits and outlets, as is common practice on most watershed models.

MOHID Land is an integrated model grouping four compartments or mediums - atmosphere, porous media, soil surface and river network – moving water through the mediums based on mass and momentum balances. Atmosphere forcing provides the necessary data for imposing surface boundary conditions i.e. precipitation, solar radiation, wind, air temperature and moisture. Surface land is described by the 2D horizontal grid used by the porous media module. The surface elevation is specified in each grid cell centre using a digital terrain model (DTM). Porous media is computed as a 3D domain with the same horizontal grid as the surface runoff layer, and a vertical grid, allowing variable layer thickness. The river system is defined as a 1D network extracted from the DTM and formed by reaches linking surface cell centres.

MOHID model uses a finite-volume approach for computing state variables and fluxes. Each grid cell is a control volume, being the state variables computed in their centres and the fluxes and associated variables on the cell faces. Surface runoff over the ground and river network is solved using the full St. Venant (Equation (1)) and mass conservation equations (Equation (2)).

St. Venant equation

$$\frac{\partial Q_i}{\partial t}+\frac{\partial u_j Q_i}{\partial x_j}+gA\left(\frac{\partial h}{\partial x_i}\right)-gA\left(S_0-S_f\right)_i=0 \tag{1}$$

Mass conservation equation

$$\frac{\partial Vol}{\partial t}+\int\limits_{S_{Vol}}(u_j n_j)dS_{Vol}=0 \tag{2}$$

where Q is water flow ($m^3\,s^{-1}$), u is the water velocity, A is the cross flow area (m^2), g is gravity acceleration (ms^{-2}), h is water depth (m), S_0 is the bottom slope, S_f is the bottom friction slope, the slope that balances the friction force, and x is the space coordinate, S_{Vol} is the surface that encompasses the finite-volume.

The porous media in MOHID Land is a 3D domain including saturated and non-saturated zones. The flow is driven by the total pressure head (H) which accounts for gravity, the matric potential in unsaturated areas and hydrostatic pressure in saturated areas. Per unit of area the flux is given by Equation (3):

Water flux in the ground.

$$\Phi_i=-k(\theta)\frac{\partial H}{\partial x_i} \tag{3}$$

where $k(\theta)$ is the hydraulic conductivity a function of the soil moisture in the unsaturated zone and a constant, the saturated conductivity, in the saturated zone. The rate of accumulation of water per unit of volume in the ground – the rate of change of soil moisture – is the integral of this flux along the surface of the finite-volume (Equation (4)):

Ground water conservation equation

$$\frac{\partial\theta\cdot Vol}{\partial t}+\int\limits_{S_{Vol}}(\Phi_i n_i)dS_{Vol}=0 \tag{4}$$

where θ is cell soil moisture content (m^3 water$\cdot m^{-3}$ soil). If this volume converges to one point, the Richards equation (Richards, 1931) for unsaturated soil is obtained. When the soil is saturated, there is no water accumulation and the integral of the fluxes is zero.

Vegetation growth was computed using the SWAT model vegetation module, based on the heat units concept that drive the plant activity and using crop database for plant potential growth curves (Neitsch et al., 2005). Growth is computed taking into account the limitations due to environmental constraints (i.e. water and nutrients availability, temperature, solar radiation). Potential evapotranspiration is computed using the FAO Penman-Monteith equation (Allen et al., 1998) being effective evapotranspiration computed as a function of root distribution and soil water availability.

Model's compartments are linked dynamically through fluxes computed at the interfaces. The computation of these fluxes requires some hypotheses since the equations solved in each compartment are different, even between the saturated and the non-saturated zones of the porous media. Water flux between the river and the porous media is computed using the head gradient and saturated conductivity. Fluxes between the river and land surface are computed using the free surface gradient and assuming critical flow in case of land flooding. These algorithms permit the explicit simulation of river floods and generate variable river discharge, as a function of the water content and flow along the whole catchment. At the interface between saturated and not saturated zone, there is no real physical interface but equations to compute the pressure and the conductivity change. In order to simplify the convergence procedure cells are considered as being saturated when the soil moisture is between 98% and 100%. In practice this is equivalent to assume a storage capacity as used is models for saturated soils, e.g. MODFLOW, Hoffmann et al. (2003).

Dissolved properties transport in the soil, at surface by runoff and in the river is described by the advection diffusion equation (Equation (5)) where β is any property concentration (mgl^{-1}), ϑ is diffusivity ($m^2\ s^{-1}$) and (S_o-S_i) is difference between the sources and the sinks of β integrated inside the finite-volume.

Advection–Diffusion Equation

$$\frac{\partial\theta\cdot\beta\cdot Vol}{\partial t}+\int_{S_{Vol}}\beta(\Phi_i n_i)dS_{Vol}=\int_{S_{Vol}}\left(\vartheta\frac{\partial\beta}{\partial x_i}\right)n_i dS_{Vol}+(S_o-S_i) \qquad (5)$$

In order to simulate carbon, nitrogen and phosphorus cycling in soil, the Root Zone Water Quality Model (Ahuja et al., 2000) was coupled to MOHID Land thus being able to represent soil bacteria activity that drives mineralization, nitrification and denitrification processes. The decays rates are dependent on temperature, salinity, nutrient availability, substrate and carbon in the case of heterotrophs.

MOHID Land computes algae activity, nutrient assimilation, mineralization, nitrification/denitrification processes taking place in rivers using an algorithm initially based on the WASP model (Wool et al., 2001) that has been updated to simulate extra processes (Mateus et al., 2012), including macroalgae (Trancoso et al., 2005) and the competition between these and benthic herbs (Ascione–Kenov et al., 2013).

Regarding particulate material transport in river and surface runoff, the erosion/deposition processes are calculated based on Partheniades (1965) depending on surface shear, sediment strength and deposition velocity. Erosion occurs when the ambient shear stress exceeds a limiting threshold and deposition occurs when the ambient shear stress is lower than that specified threshold (Trancoso et al., 2009; Franz et al., 2014). Table 1 summarizes the model main parameters, their typical values and references.

MOHID Land has been applied from plot to watershed scales. At a watershed scale the model was used in the FP7 ‘MyWater’ research project focused on obtaining reliable information on water quantity, quality and usage for appropriate water management. The model was applied to Tâmega River in the Douro watershed, Portugal, to quantify water input to the reservoir and model results were compared to available data (http://mywater-fp7.eu/). Furthermore, MOHID Land model was applied in an integrated approach with the reservoir model MOHID Water and SWAT in Enxoé, Portugal to depict the origin of this eutrophicated reservoir and its results compared to field data (Eutrophos https://eutrophosproject.wordpress.com/, Mirage http://www.mirage-project.eu/and Aguaflash http://www.aguaflash-sudoe.eu/research projects). The model was also applied to natural wetlands, Ebro and Bidasoa in Spain, Garonne (France) and Tagus (Portugal), to determine natural depuration potential and its results compared to piezometer data in the context of Attenagua project (http://www.attenagua-sudoe.eu/).

An example of a plot scale implementation is the Nitrosal project, created to determine salinity effect on crop production and where the model was applied to a 1D soil column in Alvalade (Portugal). Other examples include Aquapath-Soil (www.agro-evapo.eu) and Figaro (www.figaro-irrigation.net/). European research projects, which aimed at crop optimization and end-user support.

3.3. Operational modelling

The pre-processing of meteorology, model preparation and execution and model post-processing are handled by the operational Automatic Running Tool (ART), a software for model simulations automation developed at Instituto Superior Técnico. The ART tool pre-processes inputs from different sources needed to run the model; executes the Mohid Land using the configured files and store, graphs and distributes the model results via OPeNDAP, smartphone and Webpages (Fig. 2). The simulated period started in January 2010 and is currently running and producing forecasts for both domains that can be accessed at http://forecast.maretec.org/.

4. Results and discussion

In order to validate the methodology, modelling results were compared with river monitoring data from the Portuguese National Institute for Water (INAG) published in their portal SNIRH (http://www.snirh.pt). Due to the monitoring network constraints regarding availability and quality of the observed data for the current decade, the meteorological data was obtained from the internet database tutiempo.net (http://www.tutiempo.net).

Monthly averaged meteorological and hydrological data, including nutrient concentrations were compared with model results to evaluate the model ability a) to represent the main trends in observed data and b) to forecast river loads to coastal areas, which is one of the main objectives of the models implementation. Several monitoring stations near the each river mouth were selected to evaluate the meteorological, river flow and water quality properties

Table 1
MOHID Land model parameter description.

Parameter description	Variability	Values	Reference(s)
Manning-Strickler's roughness coefficient	From land use map	0.01 to 0.3	Van der Sande et al., 2003, Chow 1959
Impermeable Area (%)	From land use map	0.5–1 in urban, artificial areas and 0 in forest and agricultural areas	–
Feddes vegetation stress heads (m)	From land use map	−0.01 to −30	Feddes et al., 2001
Soil van Genuchten hydraulic parameters	From soil map database	–	–

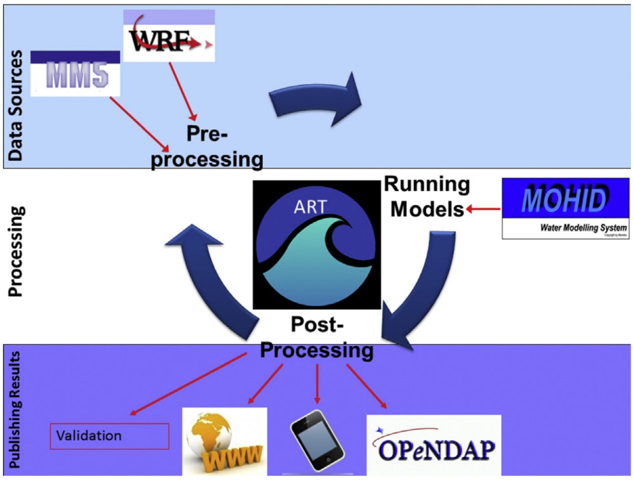

Fig. 2. General scheme of the Automatic Running Tool (ART) where it can be distinguished the pre-processing, modelling and post-processing cycle of operations including only elements used for the WI and IP Mohid Land applications.

as no single stations collect all these properties.

The IP domain modelling results were evaluated by comparing the modelling results for the Tagus River, the longest estuary of the Iberian Peninsula, with atmospheric and hydrometric observations. Precipitation results obtained from the WRF model application were compared with the Castelo Branco station (M1 in Fig. 1, 39.83N and 7.48W) in the Tagus catchment. The modelled river flow was compared with the streamflow measured at Almourol station (F1 in Fig. 1, 39.22N, 8.67W), located 70 km off the head of the estuary. The Ómnias station data, located some 30 km downstream from the Almourol station was used to validate water properties.

The largest Portuguese non-transboundary river, the Mondego River, was used for evaluating the WI domain modelling results. The Açude de Coimbra station located in the city of Coimbra (F2 in Fig 1, 40.22N, 8.44E) located around 40 km afar from the coast, was used to perform flow and water properties validation and the Viseu station (M2 in Fig 1, 40.71N, 7.88E); was used to assess the MM5 precipitation results.

4.1. Meteorology and hydrology for the Tagus and Mondego rivers

Monthly averaged observations and modelling results – precipitation and flow - for the Tagus and Mondego rivers are shown in Fig. 3 for the period between January 2011 and December 2013. Table 2 shows the statistical parameters for the comparison of meteorological and watershed modelling results and field data observations. Precipitation computed by MM5 (9 km grid) and WRF (12 km grid) display a similar agreement with the data being both able to match most of the rain events. They are able to represent the main trends of the automatic monitoring stations and display peaks with identical magnitude both achieving coefficients of determination (R^2) around 0.9 as a consequence it can be concluded that both MM5 and WRF models for the WI and IP domains respectively reproduce significantly the precipitation patterns observed in the data collected by tutiempo.net (Fig. 3a and b) and are adequate to force the hydrological models. Both stations present a similar distribution of rain for the studied periods as rainfall is associated to the same originating mechanism though peaks are more intense in the Mondego watershed and presenting on average a larger abundance of precipitation following the typical North to South pattern present in the Portuguese territory.

Modelled streamflow shown in Fig. 3(c and d) follows a pattern consistent with the rainfall (Fig. 3a and b). We should take into consideration that the modelling results are reproducing the watersheds without any human intervention apart from nutrient input due to agricultural practices and thus water removed from their courses for irrigation, human consumption or accumulated in water reservoirs and dams are not considered in this first version of the model.

During the dry season flows are low and thus measured and simulated values are almost identical. The model predicts an increase in flow values as soon as the raining season in autumn starts, however measured values remain low. In winter and spring the agreement increases again. The difference of behaviour between measured and simulated discharges is attributed to the fact that after the summertime reservoirs storage is at its minimum and consequently they accumulate most of the inflowing water. In winter, reservoirs are close to their maximum capacity so they collect a lower portion of the rainwater and thus the river flow is similar to its natural flow.

In Fig. 4, river modelled flows from the WI and IP domains are compared with observations for the Tagus River station (F1 in Fig. 1). The WI river flow would correspond to the rain water collected mainly in the Portuguese territory (Fig. 1), assuming that no water is flowing from Spain, while the IP river flow would correspond to the complete watershed. In this figure, it can be observed that both curves coincide during the dry periods, while the observed values are closer to the WI flows after the beginning of the rain periods, indicating that most of the water is retained upstream, and as the rainy season progresses the observed values approaches the IP curve indicating that the reservoirs are close to reach their full capacity and the river discharge is similar to the natural flow. It can be concluded that discharges computed in autumn without considering the reservoir storage would be overestimated. This effect would increase along with the catchment size. If the Tagus River is regarded considering only its Portuguese part of the catchment, the forecasts improve, except during rainy winters. This means that the impact of the Portuguese reservoirs on the discharge is much lower than the impact of the Spanish reservoirs, as 70% of the catchment is located in Spanish territory.

In any case, the modelled flow for the whole Tagus and Mondego catchments, without considering reservoirs storage, obtained satisfactory R^2 values around 0.6 (Table 2). This range of values are similar to the ones obtained in similar case studies as Yang et al. (2014) obtained for 3 watersheds from 30 to 300 km^2 in USA. However, in natural watersheds values of R^2 values usually range from 0.6 to 0.9 as the works of Fohrer et al. (2001) in two watersheds in Hesse, Germany (R^2 of 0.71 and 0.92), Geza and McCray (2008) in a 126 km^2 watershed in Denver, USA (R^2 of 0.62 and 0.74) or Green and van Griensven (2008) in small watersheds in Texas, USA (R^2 0.60 to 0.96). The modelling results could be improved by including the effect of the reservoirs in the simulations. For that reason, the modelling results would tend to be closer to the observed values as the degree of human intervention is lower.

Fig. 5 shows the Mondego river flow, observed and modelled, and the water level in the Aguieira Reservoir (40.34N, 8.20W), the main reservoir in the catchment. This reservoir is used for power generation, flood control, water supply and irrigation. The figure shows that when the model computes excess flow the level in the reservoir increases. This result explains the origin of the differences between measured and computed flow and indicates the importance of the inclusion of reservoirs in future versions of the hydrographic model. The scenario without reservoirs had the advantage of illustrating their impact in the system. Additionally, in Fig. 5 can be observed how the reservoir volume decreases during

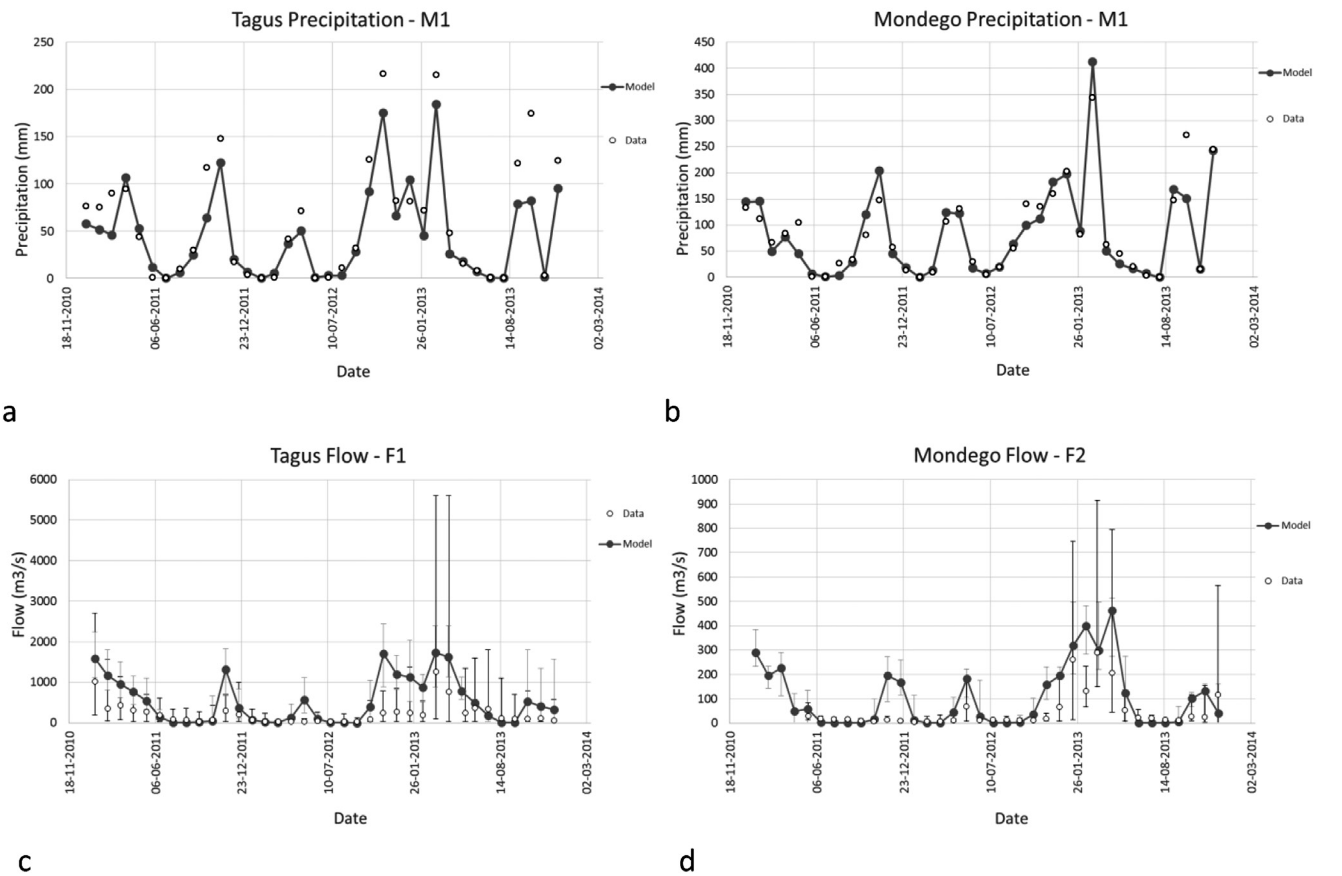

Fig. 3. Monthly averaged modelling results (solid line) and observations (white circles) for the Tagus River (left side) and for the Mondego River (right side) for precipitation (top) and river flow (bottom) for the period 2011–2013. The graphs include error bars for flow observations (black bars) and for the flow modelling results (grey bars). Error bars for model precipitation are not visible, as the standard deviation values are too small.

Table 2
Statistical parameters for the meteorological and hydrometric monthly averages corresponding to the Tagus and Mondego Rivers watersheds in the period 2011–2013 (n = 36).

Station	Watershed	Type	Obs. average	Model. average	R^2	RMSE
Viseu	Mondego	Meteo	86.00 mm	84.08 mm	0.88	30.91 mm
Castelo Branco	Tagus	Meteo	59.77 mm	55.19 mm	0.90	19.83 mm
Açude de Coimbra	Mondego	Flow	48.76 $m^3 s^{-1}$	93.59 $m^3 s^{-1}$	0.60	93.77 $m^3 s^{-1}$
Almourol	Tagus	Flow	228.59 $m^3 s^{-1}$	533.71 $m^3 s^{-1}$	0.59	495.98 $m^3 s^{-1}$

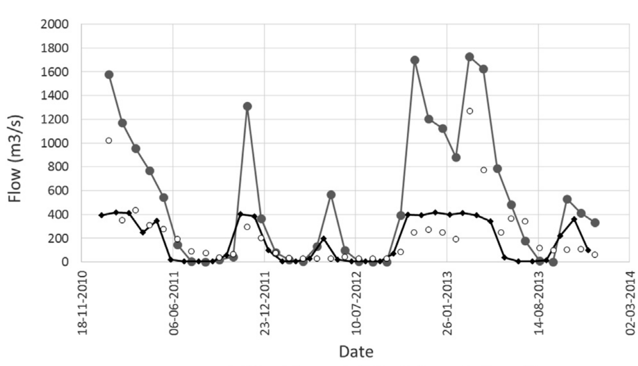

Fig. 4. Monthly averaged modelling results for the Iberian Peninsula domain (solid grey line) and for the Western Iberia domain (solid black line) and observations (white circles) for the Almourol station in the Tagus River (F1 in Fig. 1) for the period 2011–2013.

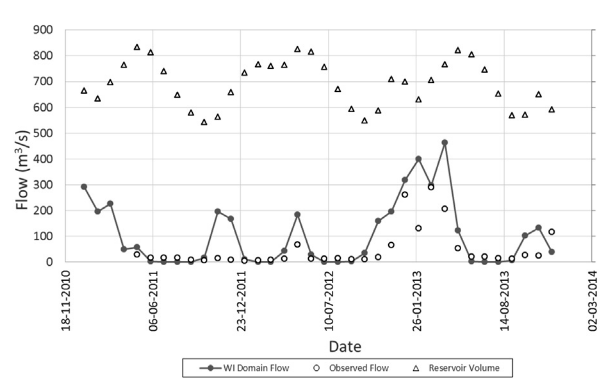

Fig. 5. Monthly averaged modelling results for the Mondego River (solid line), observations (white circles) and volume accumulated in the Aguieira reservoir (white triangles) for the period 2011–2013.

the summer period due to human consumption as that volume has no impact in the observed river flow.

4.2. Water properties for the Tagus and Mondego rivers

Regarding the water properties of the water running in these two rivers, the modelling results for temperature and dissolved nutrient concentrations, nitrate and orthophosphate, were compared with observed values. It should be noted that the number of water quality observations and the limit of detection of the measured are poor to evaluate the water quality on those watersheds. We should also bear in mind the different horizontal model resolution of the modelling domains.

In Fig. 6 are represented monthly averaged measured and computed variables describing water quality for both catchments and in Table 3 describes some statistical indicators. Visual analysis of the figures show that temperature is better described in the Mondego than in the Tagus, nitrate is well described in both catchments apart from two abnormal peaks in both catchments and phosphate is poorly described in the Tagus River water quality station. The temperature and orthophosphate measured values in this Tagus station are usually above the computed, being both abnormally high values for the study area. Both nutrients in the Mondego model present peaks simultaneously during low discharge conditions that were preceded by high flow conditions (Fig. 6 d and f). These concentrations are the result of the mineralisation of the particulate organic matter previously transported by the high run-off. As the water column is low, a small mass of

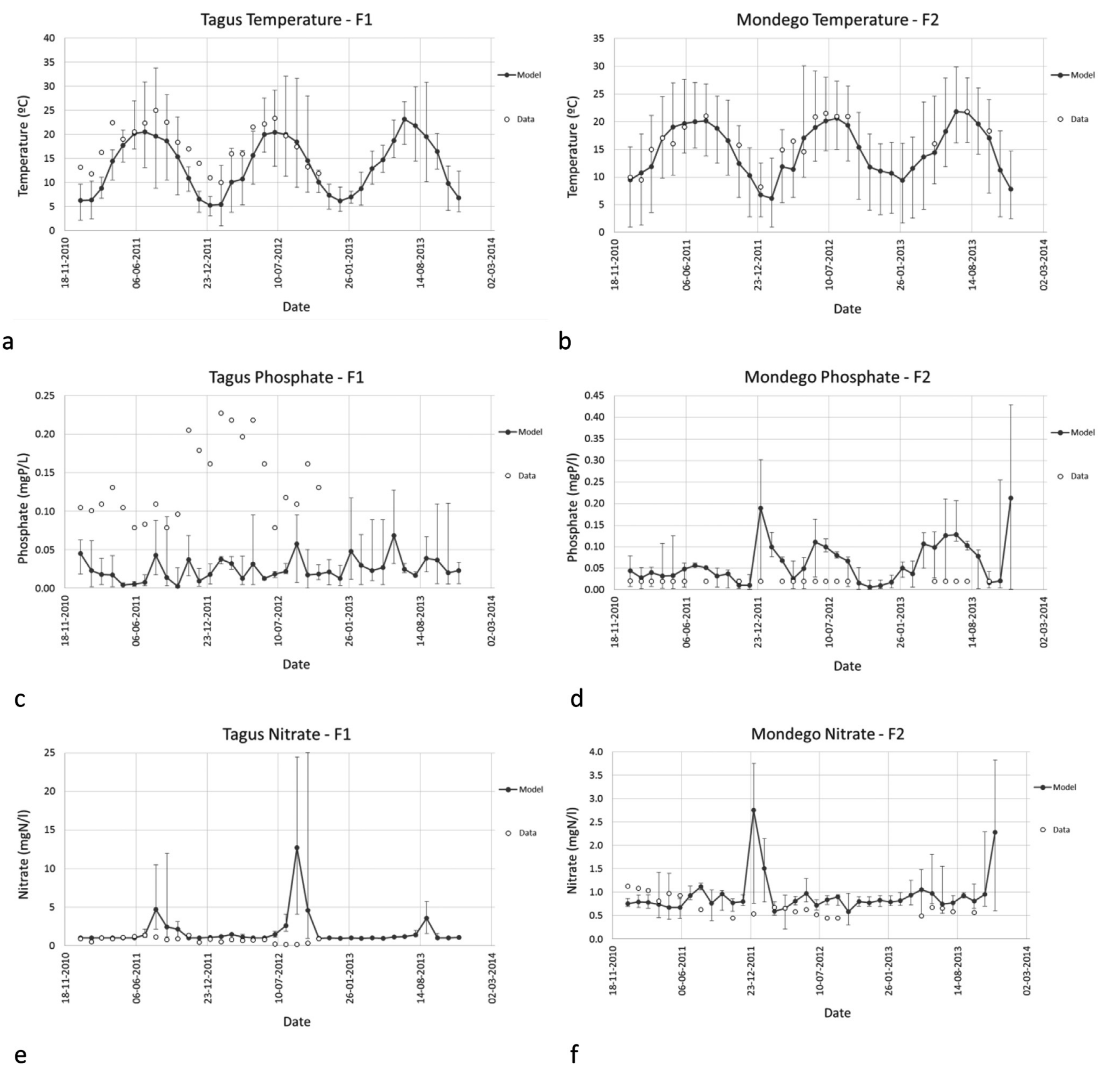

Fig. 6. Monthly averaged modelling results on river water quality (grey line) and station field data (white circles) for the Tagus River (left) and Mondego River (Right); a) and b) temperature (°C); c) and d) orthophosphate (mg P l^{-1}); e) and f) nitrate (mg N l^{-1}). Error bars are only shown for modelling results as the observed values correspond to monthly samples.

Table 3
Simple statistics for the comparison between the observations (Obs.) and modelling results (Mod.) of water properties: temperature (°C), nitrate (mg N l^{-1}) and ortophosphate (mg P l^{-1}) for the 2011–2013 period.

Watershed	Property	Obs. N	Mod. N	Obs. average	Mod. average	R^2	RMSE
Mondego	Temperature (°C)	34	23	16.80	15.10	0.80	5.40
	Nitrate (mg N l^{-1})	36	23	0.70	0.89	0.11	0.38
	Orthophosphate (mg P l^{-1})	32	23	0.02	0.05	0.02	0.05
Tagus	Temperature (°C)	37	23	18.00	14.00	0.75	6.20
	Nitrate (mg N l^{-1})	35	23	0.92	1.80	0.16	2.80
	Orthophosphate (mg P l^{-1})	36	23	0.14	0.02	0.07	0.02

organic matter is able to increase the nutrient concentrations. In the observed nutrients concentrations, the raise was not detected possibly by two reasons: (a) on one hand that high flow was retained by the water reservoirs and (b) in case that part of the organic matter arrived to this reach, the small amount of nutrients could be consumed by benthic primary producers, especially by macrophytes existing along the river bed and not taken into account by this model. The same explanation serves for the peak observed in the Tagus River in August 2012.

4.3. Portuguese river loads

The numerical modelling approach proposed in this study provides the capacity of modelling simultaneously all the watersheds of a certain region delivering an overview of the fresh water reaching the coastal area in terms of flow, temperature and nutrients. Considering that the average volumes and nutrient concentrations for the analysed rivers are correct on average, it was estimated the average annual load for each of the twenty five largest rivers discharging in the Portuguese coast (Table 4). The WI domain was used for most of the Portuguese catchments while the IP domain for the main international rivers: the Douro, Tagus and Guadiana rivers. Table 4 list the fluxes in terms of volume and inorganic nutrients at the end of their watercourse thus obtaining, for the first time, the flow and nutrient budget discharged in the Portuguese coast.

In total, the main twenty five rivers flowing into the Portuguese continental coast discharge in average ca. 82000 H m^3 of fresh water, 215000 Tons of dissolved inorganic Nitrogen and 3300 Tons of dissolved inorganic phosphorus per year. From Table 4 figures, it could be concluded that in natural conditions the Douro River accounts for a third of the nutrients and flow contributions while the Tagus River and the Guadiana River account approximately for the fourth part of the natural contributions to the Portuguese coastal area. All together the small unmonitored rivers represent about 12% of the forecasted discharge for all rivers and thus they also play a relevant role in the coastal areas.

5. Conclusions

Governments worldwide are reducing their efforts in collecting reliable and widespread hydrometric information, which would affect in decision making related to water supply, hydropower, irrigation and other services including drought and flood events warnings or unforeseen adverse impacts on other users (i.e. water logging, salinization, impacts on wetlands, lakes, floodplains, and estuaries) (Mishra and Coulibaly, 2009). This decline, also observed also in Portugal, should be compensated by new methods to complete the information collected by the remaining stations or to produce an estimate value in the watersheds where information is totally absent. In this study, we have explored the use of a numerical model as a valuable tool for completing the observed data.

Table 4
Average river runoff and dissolved inorganic nutrients for the rivers discharging in the Portuguese continental coast during the 2011–2013 period obtained by the MOHID Land simulations. (IP) stands for Iberian Peninsula domain results and (WI) for West Iberia domain results. Rivers are ordered from North to South.

River	Average runoff (Hm^3 y^{-1})	Dissolved nitrogen (Ton y^{-1})	Dissolved phosphorus (Ton y^{-1})
Minho (WI)	7730	15665	172
Lima (WI)	2120	8255	150
Cavado (WI)	1581	3605	27
Ave (WI)	1241	2775	47
Leça (WI)	120	203	4
Douro (IP)	29,359	75049	1119
Vouga (WI)	1869	4447	79
Mondego (WI)	3269	8238	204
Lis (WI)	312	866	23
Alcobaça (WI)	162	334	11
Tornada (WI)	68	176	5
Arnoia (WI)	127	374	11
Grande (WI)	239	399	6
Sizandro (WI)	109	273	9
Lisandro (WI)	67	185	6
Tagus (IP)	16,767	43266	413
Sorraia (WI)	624	1772	52
Sado (WI)	1255	3438	105
Mira (WI)	357	957	18
Odeceixe (WI)	65	150	3
Aljezur (WI)	42	93	2
Arade (WI)	148	411	8
Alcantarilha (WI)	214	495	9
Alcantarilha (WI)	214	495	9
Guadiana (IP)	13,889	42796	843
Total	**81,734**	**214221**	**3327**

The complex pattern of precipitation and hydrology put in evidence the need for sophisticated tools to represent reality and fill conventional data gaps as for the use of modelling. For that reason, we considered that this type of application is valuable tool as a complement to any observing system and also could aid in the explanation of the field data measurements. In this study, the water resource availability in an internationally managed watershed and the fate of rainfall water in a national watershed were used as case studies to show the possible analysis applications that this methodology could support.

Traditionally, watersheds models have been used to reproduce the flow and water properties of a single river catchment while in this new approach the modelling domain could present several outlets that allow to calculate several catchments simultaneously and to obtain the “big picture” of fresh water flow and concentrations for a vast area as the whole Portuguese continental territory or Iberia. This method is generic and could be applied to any region regardless the size or the number of catchments as have been demonstrated with the application with two different horizontal scales to the Portugal and Galicia region and to the complete Iberian Peninsula. With the described architecture, the MOHID Land application is able to estimate the natural flow running in the water lines thus disregarding human consumption, water reservoirs and dams that could influence the amount of water reaching the coastline. These processes would be taken into account in future developments along with further validations in other catchments.

The model was able to represent flow trends and order of magnitude, even at artificialized rivers, of flows and nutrient concentrations and temperature, being a good estimator of the fresh water inputs to the coast. The approach followed to link watershed and coastal models is novel and constitutes a valuable tool for filling data gaps, understanding the nutrient budgets, paths, fate and effect on coastal area and to produce forecast and scenario testing capability, a valuable asset towards an integrated water management. The modelling results are directly used by other downstream models in coastal and estuarine areas producing an original methodology for integrating the water management from the catchment to the open ocean that would be discussed in future research papers (Campuzano et al., 2014).

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