The use of catchment models coupled with weather forecasts to support water management in Mozambique Umbeluzi watershed

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ABSTRACT

The Umbeluzi River basin has a total area of 5458 km^2, which 40% are located in Mozambique, 58% in Swaziland and 2% in South Africa. In terms of topography, about 20% of the area is above 500 meters, peaking at 1800 meters. The western is mountainous, followed by a plain area which concentrates the production of sugar cane crop and a small mountain range (Pequenos Libombos). In Umbeluzi watershed there are two dams, which have an important role: Mnjoli in Swaziland and BPL (Pequenos Libombos dam) in Mozambique. The first one is needed for irrigation of mainly sugar cane areas, and the second one is essential for water supply in Maputo.

To support water management in Umbeluzi watershed, a platform to manage available data and models will be developed in the context of MyWater FP7 project (http://mywater-fp7.eu/). This platform will be developed to support the water stakeholders in their decisions.

One of the models is managed by this platform is SWAT model, a basin hydrological model which vastly used around the world. This model calculates the water balance at watershed scale. Another model that will be implemented is Mohid Land which is also a catchment model with the advantage of having a sub-daily time step that makes it useful for sub-daily events like floods.

For the hydrological characterization of this basin it was used available datasets that include topographical map, soil type and land use map, meteorological and flow data.

Models were calibrated and validated with available flow datasets from gage stations. Additional validation was produced comparing model results of evapotranspiration with evapotranspiration obtained with SEBAL model that uses satellite data as input. A good validation of the model guarantees high reliability and accuracy of the water balance in the watershed that will support water management. The possibility of predicting the water balance can also support managers in decision making. Because of that, model will also be run in a forecast mode using as input results from weather forecasts models like GFS - Global Forecast System (http://www.emc.ncep.noaa.gov/) and ETA model implemented by CPTEC (http://www.cptec.inpe.br/). Comparisons of model results using both weather forecasts as input will be presented.

KEY WORDS: *Water management, forecasts, MOHID Land, SWAT.*

INTRODUCTION

Billion of people have no adequate access to water (WHO, 2012), and climate changes lead to dramatically changing water resources availability and needs (Arnell, N., 1999). These changes will influence all citizens, and authorities will need more reliable information to adapt to the new situation. In particular case of Umbeluzi watershed, water supply in Maputo city relies on water quality and quantity of Pequenos Limbombos Reservoir. This reservoir depends on contribution from whole watershed that is shared with Swaziland and has high density of irrigated agriculture, flooding and strong water scarcity problems (ARA-Sul, 2000 & SWECO *et al*., 2003).

MyWater project responds to these challenges, implementing a new information platform which integrates data from three scientific research areas – earth observation, meteorology and catchment modelling – to better assess hydrological processes. Earth observation satellites are used to identify Land Cover Land Use (LCLU), measure Leaf Area Index (LAI), Evapotranspiration and Soil Moisture. On the other hand catchment models can estimate these parameters and allow confirming or complementing the satellite data. Meteorological data will provide information related to water availability (e.g. precipitation). The integrated use and improvement of the different information sources is expected to result in high reliability and accuracy of water services. The aim of this work is to produce reliable information on water use, mainly water quantity at watershed level. For that, calibrated models and accurate data are needed.

METHODS

It is presented in this section the methods used in this work. A brief description about MyWater platform, the site implementation (Umbeluzi watershed) characterization, and MOHID Land and SWAT models, is presented. A description about SEBAL model can be found in Bastianssen *et al*., 1998 or Alexandridis *et al*., 2009.

MyWater platform

Some of the users of the MyWater project don't have the computing resources to maintain continuous data collection and processing services. MyWater project will supply this as a service. User can connect to MyWater platform and select relevant data sources along with the sort of treatment they want to apply to these sources (alarms, reports, etc).

MyWater data platform is divided into server and client (Figure 1). The server is a collection of cloud services to manage environmental data. The client is a web portal where users can configure and consume these services.

This software tool is responsible for gathering or indexing disperses sources of environmental data, and provides a single point of access. Over this catalog of data the platform will automate the execution of mathematical models or other data processing tools, report generation and alarms.

To allow multiple front-ends, the platform will expose its functionalities as services.

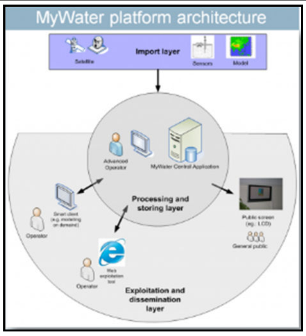

Figure 1. Mywater platform architecture

Umbeluzi watershed characterization

The Umbeluzi River basin has a total area of 5458 km2, which 40% are located in Mozambique, 58% in Swaziland and 2% in South Africa. In Umbeluzi watershed there are two dams (Figure **2**), which have an important role: Mnjoli in Swaziland and BPL (Pequenos Libombos dam) in Mozambique. The first one is needed for irrigation of mainly sugar cane areas, and the second one is essential for water supply in Maputo. The western part of the watershed is mountainous, while the central part is a plain area which concentrates the production of sugar cane crop. A small mountain range (Pequenos Libombos) separates the central plain area from the coastal plain are to the east.

Climatological data are scarce taking into account the variation of topography in the basin, mainly on Swaziland part.The Mozambique part of the basin is characterized by hot and humid climate, with the annual average temperature of around 23°C and an annual precipitation of about 700 mm (data provided from INAM – National Institute of Meteorological from Mozambique)..These averages considered the period from 1979 until 2010. Higher precipitation occurred in months with higher temperatures: December, January and February.

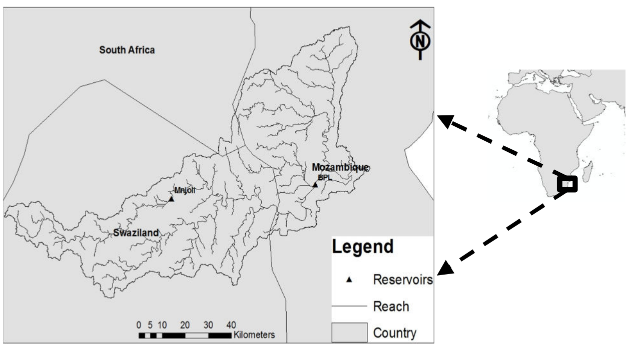

Figure 2. Umbeluzi watershed location

In years with more precipitation the average is about of 1400 mm. Due to the high precipitation events is normal that flow levels increased with consequent rivers overflow and/or dams discharges. In the year of 2000 (1999-2000 hydrological year), on February, high precipitation events result on floods in Mozambique and near countries. In the Maputo airport meteorological station, it was registered 454 mm of precipitation only in two days.

MOHID Land model description

One of the models that will be used is MOHID Land model. MOHID Land is the newest core executable of the MOHID Water Modelling System. MOHID is an integrated modeling system maintained and developed by the MARETEC (Marine and Environmental Technology Research Centre) group of Technical Superior Institute at the Technical University of Lisbon (www.mohid.com).

Mohid Land is an integrated model grouping 4 mediums (atmosphere, porous media, soil surface and river network) and water moves through the mediums based on mass and momentum balances (Trancoso *et al.*, 2009). The atmosphere is not explicitly simulated but provides data necessary for imposing surface boundary conditions to the model (precipitation, solar radiation, wind, etc.) that is space and time variant. Surface land is described by a 2D horizontal grid that can use variable spatial step. The porous media is a 3D domain with the same horizontal grid as surface, and vertical grid, also allowing variable layer thickness. The river network is a 1D domain defined from DTM by reaches linking surface cell centers (Figure 3).

Because the problems associated with floods in Maputo area, and because MOHID Land has a sub-hourly time step, it will be possible to simulate a flood event. MOHID Land has the advantage as well to use as input EO (Earth Observation) data like evapotranspiration, leaf area index or soil moisture. The use of this data is an aim in MyWater project.

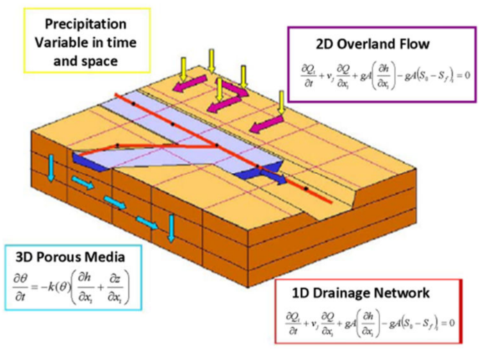

Figure 3 Mohid Land Geometry and equations

SWAT model description

The model used in this work is the SWAT model (Neitsch et al., 2005), a semi-distributed watershed model focused on land management at reach or basin scale in which a big effort and knowledge was putted in the crop database (with growth parameters of around 100 species) and vegetation growth model both developed under the knowledge of the Grassland laboratory in USDA. SWAT model divides the watershed into subareas that are assumed to be homogeneous in their hydrologic response units (HRU), uses a daily time step, and infiltration or groundwater flow is computed based on empiric or semi-empiric formulations (as the SCS rainfall-runoff curves or soil-shallow aquifer-river transfer times). The hydrology of the model is based on the water balance equation which includes runoff, precipitation, evaporation, infiltration and lateral flow in the soil profile.

The potential evapotranspiration can be calculated by the Hargreaves method (Hargreaves *et al*., 1985), Priestley-Taylor method (Priestley and Taylor, 1972) or by the Penman-Monteith method (Monteith, 1965). The last method mentioned is a standard international method widely used. The actual evapotranspiration is estimated by the sum of three components: plant canopy evaporation, plant transpiration and soil evaporation. For the calculation of transpiration is necessary Leaf Area Index (LAI). This parameter is estimated for each HRU through a model plant growth.

The relative straightforward formulation allows the model to produce in reasonable time (minutes or hours) simulations of decades in large watersheds (up to 10 000 Km^2 – e.g. Jayakrishnan *et al*. 2005). In this case, SWAT allowed to run the entire Umbeluzi watershed on a daily time step.

SWAT model input

The SWAT model was applied to the Umbeluzi watershed using the ArcSWAT interface, which is an ArcGIS extension from ESRI. Available GIS maps for topography, land use from EO data (Earth Observation data) adapt to the SWAT classification, and soils of the study area were used. Table 1 gives an overview of the input data. It was updated as well the operation schedule to the sugar cane crop: 28 September to the planting date, 32 irrigation events with 20mm of water, 8 fertilizer application (fertilizer 28-03-00), 15 May to the harvest date, and Mnjoli reservoir to the irrigation source.

Table 1. Required data and source of data for running SWAT model in Umbeluzi watershed.

Data type	Source	Data description
Topography	Shuttle Radar Topography Mission	Spatial resolution of 90 meters
Soil type	FAO-UNESCO	Soil physical properties
Landuse	Global Cover Land Use	Landuse classification
Weather	INAM	Daily rainfall; 1979 to 2011; Maputo, Goba, Moamba, Changalane and Umbeluzi stations

SWAT model calibration and validation

SWAT model includes a considered number of parameters which characterized hydrological conditions of the basin. During a calibration process, model parameters are subject to adjustments, in order to obtain model results that correspond better to the flow datasets.

In this work were tested some of the possible parameters that can influence the behavior of flow results: GW_DELAY (Groundwater delay [days]) with default value of 31, ALPHA_BF (Baseflow alpha factor [days]) with default value of 1, and SOL_Z (Soil Depth [mm]), and SOL_ZMX (Root zone depth [mm]) that are both given from the input and were tested because the uncertainty of the data.

It was concluded that only adjust the GW_DELAY (changed for the value 3) parameter can result in a good calibration. It was decreased the delay time for the aquifer recharge. Calibration and validation were made considering available flow datasets from five gage stations and respective period: Movene (1999-2009), Movene II (1996-2006), Goba (1979-2009), BPL (1979-2000) and Boane (1979-2005).

A good calibration and validation of the model guarantees high reliability and accuracy of the water balance in the watershed.

RESULTS

In this section it is presented the flow analyses made with SWAT model as well as validation of the actual evapotranspiration from model with SEBAL model. Forecasts from GFS and CPTEC were considered and compared to each other. An example of a flood event simulated with MOHID Land model for the 2000 year it is presented.

Flow analyses with SWAT model

Seventeen flow stations located at Umbeluzi river were analyzed. The drainage area, period available, the number of records, maximum and daily is presented in Table 2. The medium-high flow rates are considered uncertain in many stations analyzed. Some stations have a limited number of records.

Table 2. Flow station description with drainage area, period considered, daily flows

Flow Station	Drainage area (Km^2)	Period	Records	Daily max (m^3/s)	Daily avg (m^3/s)
Goba	3100	1951-2011	20153	833	7,9
Goba II	3184	2007-2010	647	25	3,8
Goba III	3100	1993-2000	1164	246	12,4
Movene	-	1954-2006	346	342	2,0
Movene II	703	1956-2011	6714	197	3,1
Impamputo	88	1955-2009	11929	44	0,4
Namaacha	38	1955-2011	15458	69	8,5
Namaacha II	39	1954-2011	4281	91	9,9
SMAE	5544	1951-2006	5085	71326	402,0
E.N.2	-	1956-2009	364	0	0,0
Calichane	208	1954-2011	6099	91	0,8
Calichane II	200	1967-2009	283	0	0,0
BPL Dam	3900	1959-1967	1883	59	7,8
BPL II	3900	1967-1999	6182	241	10,8
Dique de Intrusão Salina	-	1990-2006	3176	1934	13,1
Boane	5400	1954-2006	14044	147	13,2

Six stations were selected whose data flow is significant: Boane, Goba, Movene, Movene II, BPL and Calichane. Monthly average of runoff (in mm) generated by the SWAT model were analyzed in each area of influence of these points, which is compared with the precipitation of that area and the corresponding flow gauging station.

It was analyzed the annual precipitation (mm/ hydrological year) in the simulation period of 1980-2010 (31 years), for each of the precipitation stations considered in the model. For the weather stations considered, the 1984 and 2000 years were those recorded higher values of annual precipitation. As a result of intense precipitation, which occurred particularly in February, these years are characterized by the occurrence of high flooding that have caused significant impacts. To evaluate the behavior of the model related to the measures, it was considered a monthly analysis. Afterwards it was considered the monthly average precipitation for the hydrological years of the simulation period (1980 - 2010). For the six stations considered it was analyzed the periods with reliable data and consistent flow.

In Goba hydrometric station, with a drainage area of about 3059 km^2, the period between 1995 and 2009 was considered, because it corresponds to the best measured data available. The linear correlation between the flow measures and runoff from the model shows strongly positive (R^2=0.8871). In Movene hydrometric station, with a drainage area of about 1456 km^2, was considered only the 1999 and 2000 years. The flow model results in Movene are correlated with measurements (R^2=0.746). In Movene II hydrometric station, with a drainage area of about 719 km^2, the period between the 1998 to 2001 years was considered for the analysis of monthly flows. The flow model results in Movene II when compared with the measurements shows a strong positive correlation (R^2=0.8394). In Calichane hydrometric station, with a drainage area of about 139 km^2, only the 2003 year was considered for the analysis. The flow model results in Calichane has strong positive correlation with the measurements (R^2=0.8834). In BPL hydrometric station of with a drainage area of about 3762 km^2, only the year 1980 was considered for the analysis. The model results has a moderate positive correlation with measurements (R^2=0.6552). In Boane hydrometric station, with a drainage area of about 5284 km^2, the period between 1985 and 2005 was considered. The linear correlation between the measures and flow model is strongly positive (R^2=0.8661).

SWAT model coupled with forecast data (GFS and ETA)

SWAT model was coupled with forecasts data from GFS - Global Forecast System (http://www.emc.ncep.noaa.gov/) and ETA model implemented by CPTEC (http://www.cptec.inpe.br/). An average precipitation was estimated for the all watershed and for both forecast models. Precipitation data from both sources has a good correlation (R2=0.6473) (Figure 4). Considering this month, GFS estimates a total of 137 mm of precipitation and CPTEC a total of 133 mm. In spite of precipitation data from both sources is related, meteorological data such as temperature, relative humidity, wind velocity and solar radiation, can have an impact on the estimation of potential evapotranspiration (Figure 5), and therefore an impact on actual evapotranspiration. In this month, and considering the estimation from SWAT, the potential evapotranspiration obtained with GFS was 148 mm and with CPTEC was 117 mm of water. The actual evapotranspiration from both source data has a substantial difference (Figure 6), because the impact of meteorological data has in the crops. The total of actual evapotranspiration estimated with GFS was 98mm and with CPTEC was 61mm.

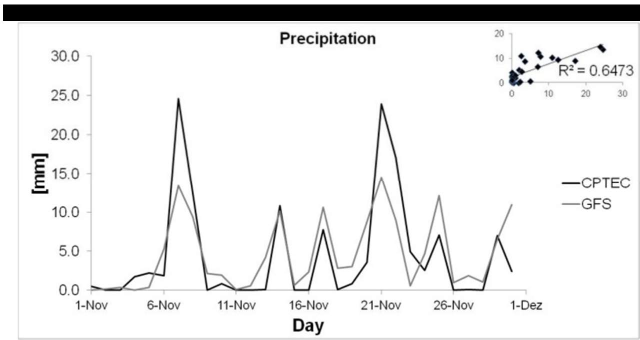

Figure 4. Precipitation data from GFS (grey) and ETA model from CPTEC (black)

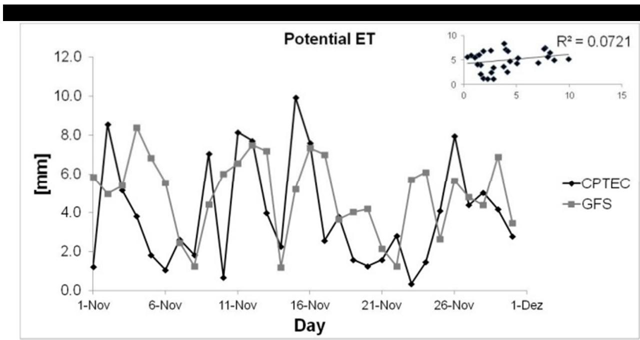

Figure 5. Comparison between potential evapotranspiration estimate with GFS (grey) and CPEC (black)

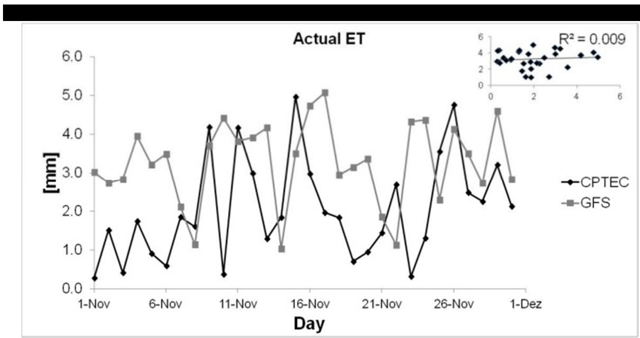

Figure 6. Comparison between actual evapotranspiration estimate with GFS (grey) and CPEC (black)

SWAT actual evapotranspiration comparison with SEBAL model

SEBAL model (SEBAL – Surface Energy Balance Algorithms for Land) estimates actual evapotranspiration each 8 days. At the moment of this paper, only data from October 2012 is available, and to the comparison it was considered the GFS run from SWAT model for that date. In average to whole watershed it can be considered a good estimation with SWAT model (Table 3). The same can said about the maximum and minimum values observed in watershed.

Table 3. Actual evapotranspiration from SWAT (a) and SEBAL (b) for each week (average, maximum and minimum)

	Average		*Maximum*		*Minimum*	
Week	a	b	a	b	a	b
Second	2.3	2.8	3.8	4.3	0.7	1.3
Third	3.5	3.2	5.3	4.7	1.8	1.3
Fourth	3.3	3.6	5.2	5.3	1.6	1.1
Fifth	3.3	3.6	4.8	5.8	2.4	1.3

Flood simulation with MOHID Land

Pequenos Libombos Dam (BPL dam), is located 35 km from Maputo city, with a total capacity of 400 hm^3. It was built between the years 1983 and 1987 and is primarily intended is water supply to the Maputo and Matola cities, irrigation (about 13.000ha), floods-damping and hydropower production. The collecting and water treatment station is located a few kilometers downstream from the Pequenos Libombos dam and the discharged constantly allow a minimum flow to the water supply.

To simulate the flood event from the 2000 year (February) it was used MOHID Land model, with two discharges, one at Movene tributary and other from BPL dam. These discharges are time series with a daily time step obtained from SWAT model (see previously on results section). MOHID Land was used considered a topography data with 90 meters of resolution, and both discharges.

Considering both discharges that were calibrated and validated in SWAT model, it is observed the impact on water column near Boane city and especially near water station (Figure 7). In this work the aim of the simulations with MOHID Land is to have more detail with more input data such as Earth Observation data (such as leaf area index, evapotranspiration and soil moisture) or output from others mathematical model as is shown in this work.

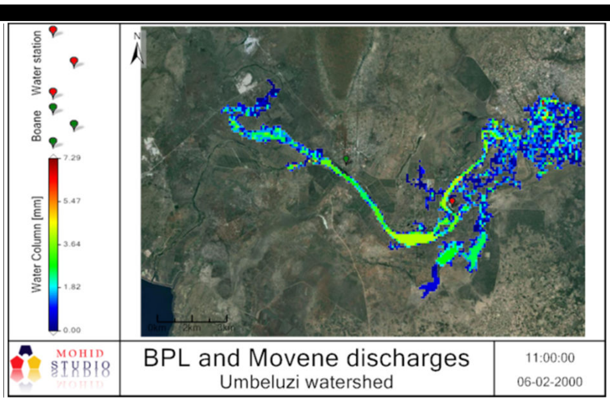

Figure 7 MOHID Land simulation with Movene and BPL discharges

CONCLUSION

This work shows the importance that reliable data has in modelling activity. Because of scarcity in data from forecasts and EO data for this site some validation is still incomplete.

It can be concluded that the results obtained with SWAT model with precipitation data from INAM and flow measures are quite positive, observing a similar behavior between both. Correlations carried out between the model and data measurements are very good observing some cases R^2 values near 0.90 (such as in Movene, Calichane and Boane stations). Only at BPL station it is observed a poorer correlation. This is due to the impact of BPL dam has in the flow of the river and because it was only considered one year in this analysis. A larger number of gauging stations enables better calibration and validation.

The comparisons between GFS and ETA forecasts data are unconcluded because the lack of data from CPTEC, that only has allowed one month. Actual evapotranspiration estimated with SWAT model with GFS meteorological data is comparable with the data from SEBAL model. The comparisons between different data sources are extremely important in this work.

More model validations and developments will be made, to accurate results from both models (SWAT and MOHID Land) and to provide reliable information to the users through MyWater platform.

ACKNOWLEDGEMENT

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