Research article

Event-based Rainfall-runoff Simulations using GETFLOWS for Kourtimalei Catchment in Djibouti

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Abstract This work was focused on the simulation of a surface terrestrial water flow process model in the area of Kourtimalei in Djibouti using GIS, RS and GETFLOWS, a physics-based surface and subsurface fully coupled fluids flow code. A trial and error were used to calibrate the model using observed surface water level of the pond. The manual calibration was performed until the surface water level of the pond RMSE to be 0.40 m with K>0.8. Furthermore kappa coefficient was used to evaluate the agreement between the pond areas extents derived from available LANDSAT-8 images during the simulation period with the pond area extents results of GETFLOWS simulation. The analysis showed that GETFLOWS successfully simulated the surface water flow process. We conclude that the use satellite derived datasets can help calibrate and evaluate GEFTLOWS hydrologic model for an ungauged watershed like in the present case..

Keywords Djibouti, GETFLOWS, LANDSAT-8, simulation, surface runoff

INTRODUCTION

Djibouti is a typical arid country located in the horn of Africa with fluctuating and low rainfall (less than 200 mm yr^{-1}) and high temperature in summer (June to August). However, intensive rainfall has sometimes caused abrupt runoff on bare land surface, resulting in heavy flood damages along the alluvial fan. When such rainfall occurs in the closed watershed, rainfall water accumulates at the lowest point in the watershed and the ponding area can stay up for several months sometimes. Usually that ponding water is lost through evaporation and seepage in a three to six months period. Kourtimalei catchment at Grand Bara desert is a good example of a closed watershed where ponding water appears during intensive rainfall. For a period of two years (May 2012-August 2014) the local government put in place a pilot farm project in the area investigating suitable irrigation techniques and cultivation techniques. In this project, source of the irrigation water was set to be a pond collected from surface runoff of the catchment water.

The purpose of this work is to characterize the runoff process of the watershed by applying observed precipitation (and other meteorological variables), at scale of hourly interval. Therefore we created a 3D model simulating the surface flow process on the basis of spatial data (DEM, land cover, geology) along with hydrogeological and hydrological parameters and integrating into the flow computer code GETFLOWS (General purpose terrestrial fluid-flow simulator) (Tosaka et al., 2000).

METHODOLOGY

Study Area

Located near the Grand Bara desert in the southern part of Djibouti, Kourtimalei watershed records an annual precipitation that ranges approximately from 150 to 200 mm yr^{-1}. The land cover distribution covers mostly bare land with sparse shrubs (Acacias), rocks, and alluvial fan surfaces on the steep hill area. The geology of the area is comprised of alluvium sediment group along the alluvial fan or in the Petit-Grand Bara desert and of basaltic rocks like Dalha basalts (3.4-9 Myr) Stratoid basalts (1.5-3.4 Myr) (Jalludin et al., 2003) (Fig. 1). The alluvium was found to be comprised of loam, sandy loam and gravel deposit which has various grain sizes. The topography influences best explains the observable differences of the soil texture and in the infiltration capacity seen tin the catchment (Toyoda et al., 2015).

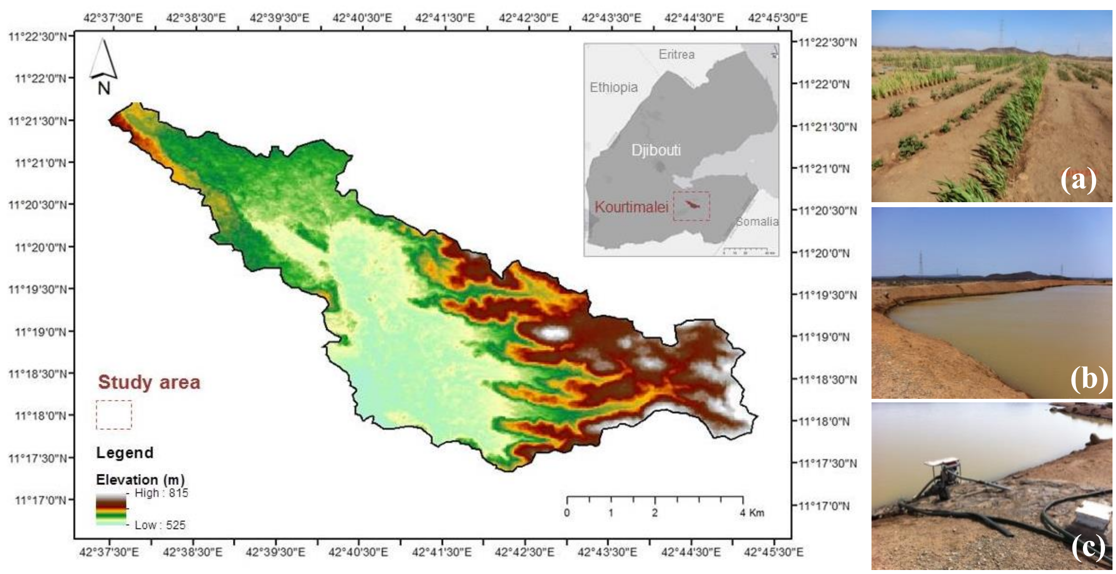

Fig. 1 Location of the study area; (a) pilot farm near Kourtimalei pond; (b) Kourtimalei pond; (c) pumping engine

As in Djibouti, precipitation is sometimes intense and causes floods therefore the government of Djibouti has decided to promote the active mobilization of surface water for agriculture. Therefore, around Kourtimalei, a pond reservoir was created (volume capacity 5,400 m^3) (Fig. 1.b) and irrigated crops have started on a small scale (pilot farm of 0.65 ha) (Fig. 1.a) with a small pumping engine (Fig. 1.c). The major problem of this source of irrigation remains the instability of the reservoir volumes. Most of the water is lost either through evaporation or seepage (JICA, 2014).

Data Collection

The key datasets enabling the implementation and testing of the numerical model are based on the widely published information but also site investigation data in the Kourtimalei basin. It includes the followings:

1) In this work, we used 4 LANDSAT-8 images (July 28, September 14 and 30, and December 03) for the pond extent mapping and the area measurements. The images represent also a crucial part of the validation phase of the simulation. It offers a good combination of two months coverage with an acceptable spatial resolution (30 m pixels).
2) ASTER GDEM data (30 m resolution DEM) published by NASA and The Ministry of Economy, Trade, and Industry (METI) of Japan was used as elevation data for the watershed area. The vertical accuracy was improved by modifying with point elevation data from ground survey in the reservoir area.
3) Observed precipitation records at different location in the watershed indicating an average of less 100 mm month^{-1}. Although the small scale of the area, it was found that the amount of rainfall isn't homogenously distributed (Toyoda et al., 2015). Evapotranspiration was estimated from potential evapotranspiration and represents 84% of the annual average precipitation.
4) Hourly record of the water level of pond collected from sensors within Kourtimalei reservoir.
5) The surface geology is from the national geology map (ORSTOM, 1986)
6) The land cover map with 3 classes (rock, soil and vegetation) was derived from LANDSAT-8 images by unsupervised classification (Fig. 1).
7) The fluid properties of water and air are represented by the typical value in the standard conditions. The soil is mainly comprised of loamy and sandy loam. The loam soil hydraulic conductivity ranges from 50 to 100 mm h^{-1}, while for the sandy loam soil texture, larger ranges (160-190 mm h^{-1}) were recorded (Toyoda *et al*., 2015)**.** The permeability of basaltic rock, weathered rock on the surface was estimated by pumping test and considered to be small as shown in Table 1 (Jalludin and Razack, 1994)

Table 1 Hydraulic parameters used

Geology	Intrinsic Permeability (cm/s)	Porosity (%)
Loamy soil	5.63 x 10^{-2}	40
Alluvium deposit	1.00 x 10^{-2}	40
Weathered rock	1.00 x 10^{-6}	10
Basalts	1.00 x 10^{-5}	10

GETFLOWS Modeling and Verifications

The General purpose terrestrial fluid-flow simulator (GETFLOWS), developed by Tosaka et al. (2000), was used to simulate rainfall runoff events at the study site. It is a physically based model that solves both the surface and subsurface systems simultaneously by employing an integral finite difference method approach for solving the governing equations. The natural system is discretized into small cells in order to obtain exact solutions (Magnus et al., 2011). The governing equation for air/water two-phase fluid flow in GETFLOWS is expressed by the following equation of mass conservation (Eq. 1).

$$-\nabla\left(\rho_p\, u_p\right) - \rho_p q_p = \frac{\partial}{\partial_t}\left(\rho_p\, \emptyset S_p\right) \qquad (p = water, air) \qquad (1)$$

Where u_p is the fluid flow velocity (m s^{-1}), ρ_p is the fluid density (kg m^{-3}), q_p is the production and/or injection rate (m^3 m^{-3} s^{-1}), $\emptyset$ is effective porosity (-), S_p is saturation degree (m^3 m^{-3}) and p is a subscripts that indicate quantities on each fluids phases. In the surface GETFLOWS solves the Manning's equation for the horizontal surface water flow by using the linearized-diffusion-wave approximation equations (Tosaka et al., 2000). The flow in the subsurface and the vertical flow in the surface are expressed with the Darcy's equation .GETFLOWS solves the saturated, unsaturated subsurface flow and surface flow in a continuum approach within a single matrix. Nonlinear interactions between all components of the system are simulated without a priori specification of the coupling between surface and subsurface flow. Therefore streams formation are purely based on hydrodynamic principles governed by recharge, topography, hydraulic conductivity and flow parameters (when water is ponded due to surfaces flux exceeding the infiltration capacity of the soil or due to excess from subsurface soil saturation).

The study area was discretized spatially in 2D plane by grid blocks of approximately 30 m. The secondary data (i.e. elevation, geology. land cover) were assigned into the corner-point coordinate of the 2D grid blocks. Then the 2D plane grid-block system was enlarged into depth direction and discretized again along Z axis to generate the 3D grid-block system. The total number of grid cells recorded to be 100,890 cells (Fig. 2).

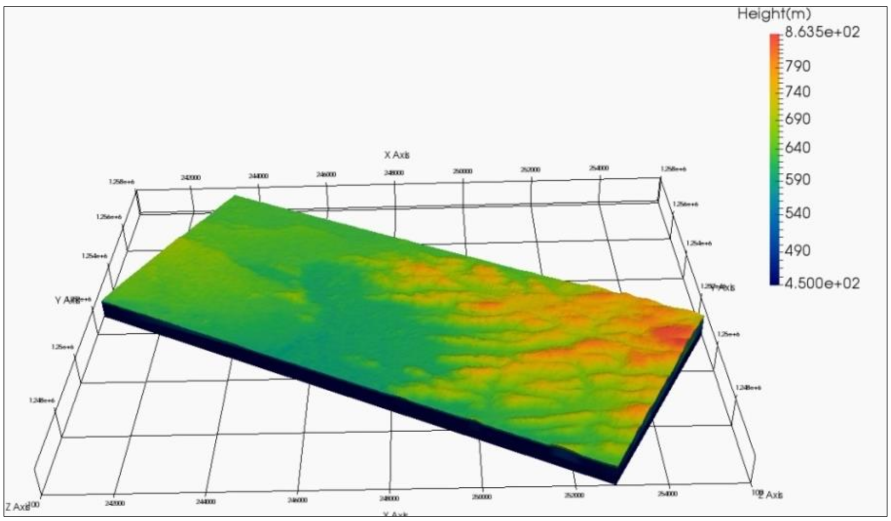

Fig.2 Three dimensional model (topography)

Our aim is to analyze the runoff characteristic of the watershed that creates the Kourtimalei pond during intense precipitation events. Thus the model was used for a short-term reproduction of the rainfall events of August 01 to December 03, 2013. Recorded daily fluctuations of meteorological conditions were constrained onto the model. Then, GETFLOWS was calibrated using the available daily pond water elevations observations for the period between August 01 and December 03, 2013 in Kourtimalei. RMSE indicator is used to assess model accuracy in matching the model-simulated runoff with observations of the differences in water level records of the pond. The criterion is used as an objective functions for the calibration. Furthermore the Kappa coefficient is used to assess the accuracy of the model by comparing the pond area extent derived from LANDSAT-8 satellite images during the simulated period with GETFLOWS simulation result at the 4 times when clear LANDSAT-8 images were available (i.e., 10 am on August 29, September 14 and 30, and December 12, 2013) (Fig. 3).

RESULTS AND DISCUSSION

In this section, we present the results of the calibration process of GETFLOWS. The Root mean squared error (RMSE) has been used for comparison of simulated pond water levels with observed water levels for the period of August to December.

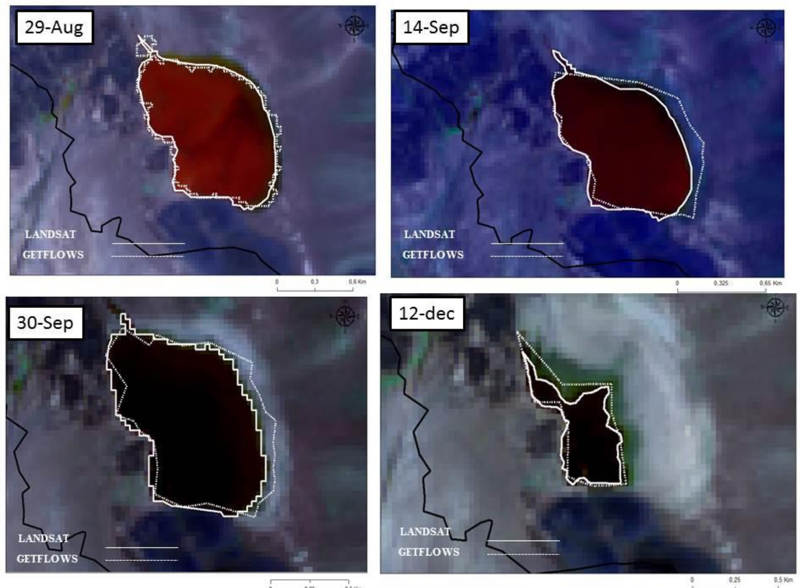

Fig. 3 LANDSAT-8 in false color (5:4:3) pond extents in August 29th, September 14, September 30 and December 12th 2013

The trial and error method yielded for an optimized parameter combination that had a RMSE of 0.40 m (Fig. 4). The Comparison of GETFLOWS-simulated spatial extent of the pond with satellite-based observations images (LANDSAT-8) (Fig3) was to provide a further evaluation of the GETFLOWS performance in simulating the spatiotemporal evolution of the pond extent during the calibration period. Fig. 5 shows the statistical comparison between GETFLOWS and LANDSAT-8 which indicates that a rather good agreement between the obtained pond spatial extents of GETFLOWS and LANDSAT-8.

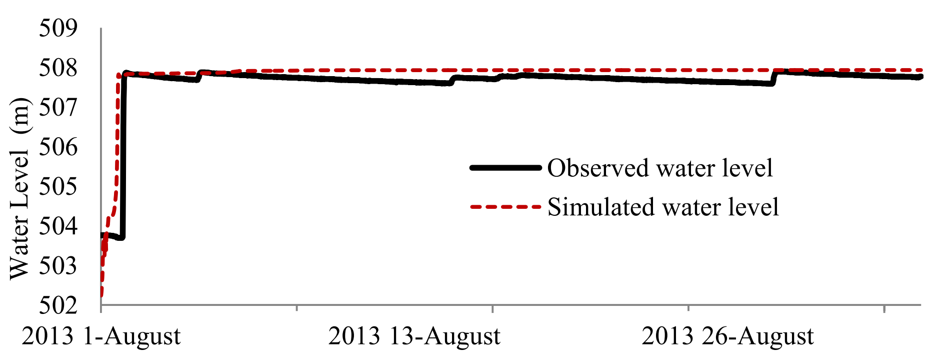

Fig. 4 Comparison between the observed and simulated water levels during the month of August, 2013

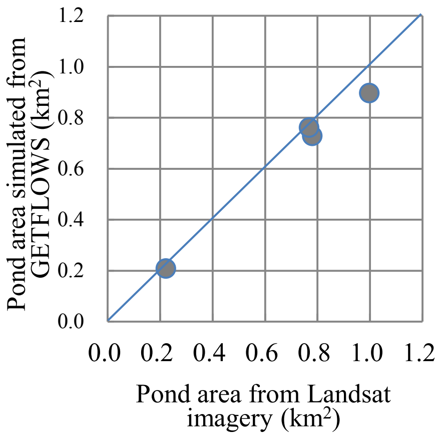

Fig. 5 Comparison of the surface pond area extent between LANDSAT vs GETFLOWS

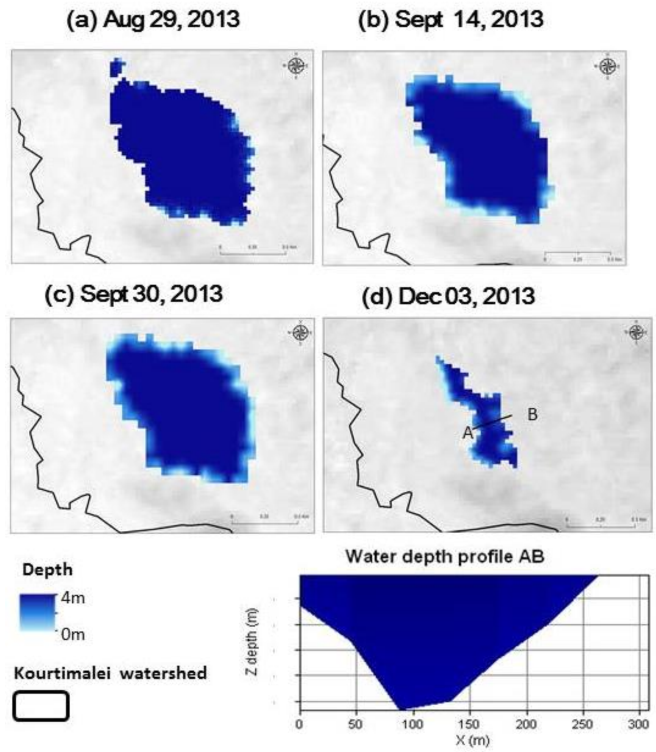

Fig. 6 Simulated water depths of Kourtimalei pond at four time step with pond profile on Dec 03

For further verification of GETFLOWS simulations results, the objective function selected to guide the agreement fit between satellite-based pond extent and GETFLOWS modeled extents was the Kappa coefficient as shown in Table 2. Overall, GETFLOWS could recreate the rainfall-runoff process successfully for each of the date. More 80% of the simulated pond extent matches the spatial extent detected by LANDSAT-8 at the given date. Less than 20% of the simulated spatial extent of the pond was either misclassified as flooded area (false) or either classified as non-flooded not all (missed).

Table 2 Comparison between GETFLOWS and LANDSAT simulated area vs derived area

Date of events	LANDSAT detected area (km^2)	GETFLOWS				Kappa Statistic *K*
		Simulated area (km^2)	Correct (%)	Missed (%)	False (%)	
29/AUG	1.00	0.90	85.64	12.16	2.20	0.88
14/SEP	0.86	0.73	80.00	13.16	6.83	0.84
30/SEP	0.77	0.76	78.86	11.03	10.10	0.83
12/DEC	0.22	0.21	71.22	6.80	21.99	0.82

CONCLUSION

In this work, we have run a rainfall-runoff simulation with GETFLOWS of the Kourtimalei watershed, and calibrated the model by using both water levels observations data, and then validated with satellite derived datasets of the spatial extents of Kourtimalei pond. GETFLOWS model was able to reproduce the rainfall-runoff process of the watershed fairly with RMSE of 0.40 m and statistics of Kappa larger than 0.8. This approach is in contrast with the conventional method of runoff modelling technique. The proposed approach implements a distributed hydrologic model and further calibrates the model parameters through satellite derived datasets that are freely available in the public domain. The impact of such a demonstrated technique is to provide a cost-effective tool in poorly gauged or ungauged watershed like in this case study.

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