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Wadi Flow Simulation Using Tank Model in Muscat, Oman

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***Abstract*— In Oman, changes in precipitation intensity and frequency have already begun to be detected, although the attributed impacts, such as, flash flooding is poorly understood. For example, the supper cyclonic storm, hurricane Gonu in 2007 led to the worst natural disaster on record in Oman, with total rainfall reached 610 mm near the cost. The cyclone and flash flood caused about $4 billion in damage (2007 USD) and 49 deaths. The objective of this study is to develop a Wadi-flow simulation model to understand precipitation-river discharge relationship in Muscat. A lumped-parameter, non-linear, rainfall-runoff model was used. The Food and Agriculture Organization (FAO-56) modified Hargreaves equation was used for estimating reference evapotranspiration (ET0). Precipitation and temperature data during 1996-2003 were obtained from the Muscat-airport meteorological station. Observed river discharges during 26-30, March 1997 were used to calibrate the model and observations during 1997-2003 were used to verify our simulations. Simulated water discharges agreed with the corresponding observations, with the Nash–Sutcliffe model efficiency coefficient equals to 0.88. This developed model will later be used with a set of General Circulation Model scenarios (GCM) to understand the Wadi-flow variations under changing climate conditions.**

I. INTRODUCTION

Oman, located in south-Eastern corner of the Arabian Peninsula, encompasses a diverse range of topography, including mountain ranges, low land, coastal areas and arid deserts. The coastal line of Oman extends over 3165 km and experiences very severe tropical cyclones. The supper cyclonic storm, hurricane Gonu in 2007 led to the worst natural disaster on record in Oman, with total rainfall reached 610 mm near the cost. The cyclone and flash flood caused about $4 billion in damage (2007 USD) and 49 deaths (Rafy and Hafez, 2008). Recently changes in intensity and frequency of the weather events and subsequent impacts demand countermeasures to adopt with these changes in future. Hydrological model is an effective tool that could provide river discharge response attributed to the changes in weather variables and can be used for planning countermeasures to cope with the potential impacts.

The tank model developed by Sugawara (1984) is a lumped parameter, non-linear rainfall- runoff model. The tank model is composed one, two, three or four tanks laid vertically in series. Various coefficients represent different hydrological processes such as surface and subsurface runoff and infiltration. The different in magnitude of these coefficients in different catchments reflects the geographical features of the watersheds. Gunawardhana and Kazama (2012) used the tank model to study water availability and low-flow analysis of the Tagliamento River discharge in Italy under changing climate conditions. Also, this tank model has been used for river discharge simulations in 12 catchment areas in Japan (Yokoo et al., 2001). Both studies were done in humid regions, but in this research, we test the performances of the tank model to simulate wadi flow in arid region in Oman.

The objective of this study is to develop a Wadi-flow simulation model to understand precipitation-river discharge relationship in Muscat (Al-Khoud catchment area). The developed model is expected to use for climate change scenarios in future studies to predict wadi flow variations under changing climate conditions.

II. STUDY AREA

Wadi Al-Khoud in Oman is located in the northern part of Oman and at the western-north part of Muscat. The downstream of catchment area is towards northeast Gulf of Oman (Fig1). The total catchment area approximately is about 1740 km2. The elevation in the catchment area ranges from 41 m at the catchment outlet in Al-Khoud to 2339 m in the inland mountain area. The climate is arid and it is important for the water resources, especially for agriculture and domestic purposes. The annul precipitation occurs in November, December, March and April as observed from previous data. The average annual rainfall in Muscat is around 63mm (Al-Khoud station) to 210 mm (JabalBani Jabir). According to the meteorological records from 1984 to 2003, the annual average maximum and minimum temperatures near the catchment outlet were approximately 33 and 24C°, respectively. The geology of the catchment area mainly consists of 55% of igneous and volcanic rocks, whereas, 3% of metamorphic rocks, 16% of sedimentary rocks and 26% of recent deposits.

III. THEORY

The tank model is a simple non-linear rainfall-runoff model composed of one or several tanks (Fig. 2). The coefficients represented for different hydrological processes (surface and subsurface runoff and infiltration) are generally obtained by matching observed and simulated data. Magnitude differences of these coefficients in different catchments reflect the geographical features of the watersheds. The rainfall summed to put into the first tank at the top. Evapotranspiration is directly subtracted from the top tank. Among the four tanks in the model, first tank at the top account for rapid runoff near the ground surface and second tank models the shallow subsurface runoff process. Other two tanks at the bottom delayed surplus water from the top two tanks.

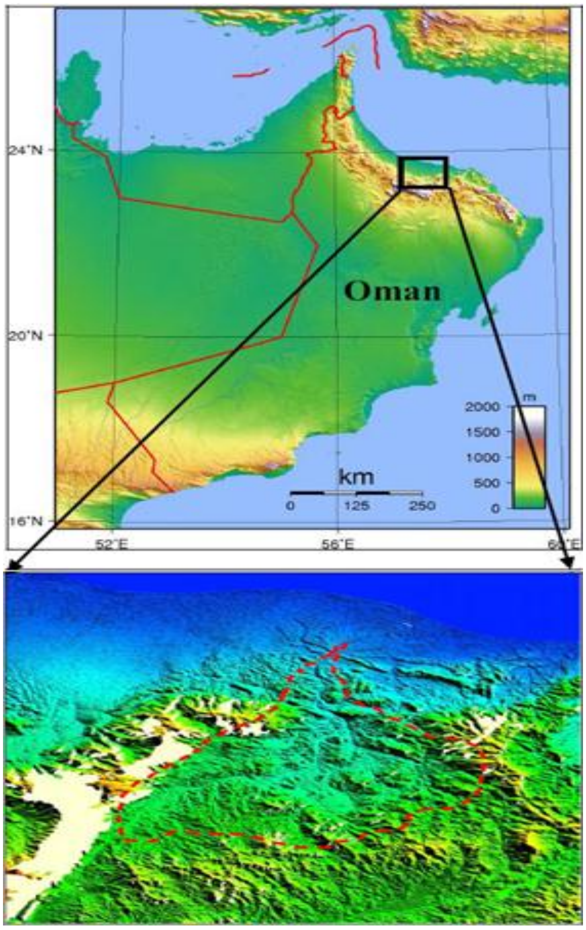

Fig. 1. Study area in Oman

This phenomenon represents hydrological role of the deep aquifers that accumulate the infiltrating water from the ground surface and released in to the downstream with certain time delays (Todini, 2007). Representative mathematical model for the water exchange between tanks and daily runoff generation can be expressed as follows.

$$R_{(x,n)} = \begin{cases} A_{(x)} \times [H_{(x,n)} - Z_{(x)}] & H_{(x,n)} > Z_{(x)} \\ 0 & H_{(x,n)} \leq Z_{(x)} \end{cases} \quad (1)$$

$$I_{(x,n)} = B_{(x)} \times H_{(x,n)} \quad (2)$$

$$H_{(x,n+1)} = \begin{cases} H_{(x,n)} - [R_{(x,n)} \times \Delta t] - [I_{(x,n)} \times \Delta t] + [T_{(n+1)} \times \Delta t] & x=1 \\ H_{(x,n)} - [R_{(x,n)} \times \Delta t] - [I_{(x,n)} \times \Delta t] + [I_{(x-1,\, n)} \times \Delta t] & x \neq 1 \end{cases} \quad (3)$$

$$T_{(n)} = P_{(n)} - Evt_{(n)} \quad (4)$$

$$Q_{(n)} = \sum_{x=1}^{4} R_{(x,n)} \quad (5)$$

where

x: number of tanks counted from top
n: number of days from the beginning (1/d)
Δt: length of time step
$A_{(x)}$: runoff coefficient of x^{th} tank (1/d)
$B_{(x)}$: infiltration coefficient of x^{th} tank (1/d)
$H_{(x,n)}$: water depth in x^{th} tank at n^{th} day (mm)
$Z_{(x)}$: height of runoff hole of x^{th} tank (mm)
$R_{(x,n)}$: runoff from x^{th} tank at n^{th} day (mm/d)
$I_{(x,n)}$: infiltration in x^{th} tank at n^{th} day (mm/d)
$T_{(n)}$: total input to first tank at n^{th} day (mm/d)
$Evt_{(n)}$: evapotranspiration at n^{th} day (mm/d)
$Q_{(n)}$: total runoff at n^{th} day (mm/d)
$P_{(n)}$: precipitation at n^{th} day (mm/d)

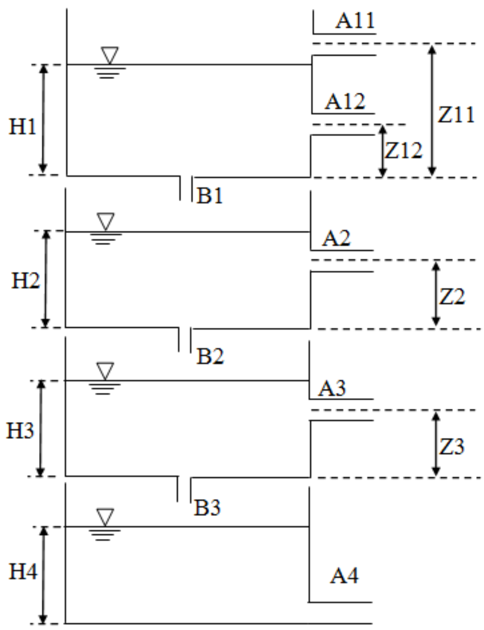

Fig. 2. Tank model structure for runoff generation

TABLE I
TANK MODEL COEFFICIENTS

Catchment area	Model parameter							
	A11	**A12**	**B1**	**A2**	**B2**	**A3**	**B3**	**A4**
Al-Khoud	0.14	0.35	0.37	0.05	0.05	0.02	0.03	0.0003
Southern Japan*	0.4	0.2	0.15	0.1	0.05	0.02	0.03	0.003
	Z11	**Z12**	**Z2**	**Z3**	**H4**	**H3**	**H2**	**H1**
Al-Khoud	1	0.1	5	10	0	0	0	0
Southern Japan*	40	15	20	10	200	40	2	1

* based on 12 catchments in southern Japan from Yokoo et al.

The Food and Agriculture Organization (FAO-56) modified Hargreaves equation, one of the widely used temperature based method, was used for estimating reference evapotranspiration (ET_0).

$$ET_0 = \frac{0.0023}{\lambda}\left(\frac{T_{\max} + T_{\min}}{2} + 17.8\right) \times \sqrt{T_{\max} - T_{\min}} \times R_a \qquad (6)$$

where $T_{\max}$(°C) is the maximum daily air temperature, $T_{\min}$(°C) is the minimum daily air temperature, R_a (MJ/m^2/d) is the extra-terrestrial solar radiation and λ is the latent heat of vaporization (2.45 MJ/m^2/d). Actual evapotranspiration was estimated by matching observed river discharge with simulations. Precipitation and temperature data during 1996-2003 were obtained from the Muscat-airport meteorological station. The Nash–Sutcliffe model efficiency coefficient is used to assess the predictive power of hydrological models. It is defined as:

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_m^t}\right)^2} \qquad (7)$$

where Q_o is observed discharge, and Q_m is modelled discharge. Q_o^t is observed discharge at time t. The closer the model efficiency is to 1, the more accurate the model is. If the simulated discharges obtained from the tank model and historical discharges have a trend and significant correlations, the simulation is considered successful and the tank model can be used to evaluate the flow phenomena for the concerning watersheds.

IV. RESULTS AND DISCUSSIONS

Model calibration was done by matching observed river discharges at gage station at the outlet of the catchment area in 1997 and the model verification was done according to data observed in 1997, 1999, 2000 and 2003 (Fig.3). Simulated wadi flow agreed with the corresponding observations, with Nash-Sutcliffe model efficiency coefficient of 0.88. Table 1 shows the calibrated model parameters in Al-Khoud catchment area. These model parameters in Al-Khoud were compared with the derived parameters in 12 catchment areas in Japan for understanding parameter dependency on different geographical and climatic settings.

The coefficients of the tank model represent different hydrological processes of the catchment. As example, larger A1 coefficient produces higher rapid surface runoff near the ground surface, while larger B1 coefficient stands for higher infiltration capacity. According to Table 1, A11 coefficient in Al-Khoud catchments is smaller than that in Japanese catchments. This is because top soil layer in Oman catchments generally has very low soil moisture content due to extreme dry condition in air and high evaporation throughout the year. Therefore, infiltration potential is higher and runoff potential in very shallow subsurface layer is low in catchments in Oman than them in Japan. For this reason, Al-Khoud catchments generate smaller A11 coefficients for the tank models than in Japanese catchments. In contrast, A12 coefficient for Al-Khoud catchment area is greater than Japanese catchment area. This can be attributed to the high representative gradient (RG) of the catchments in Oman than in Japan. Steep slope in Al-Khoud catchment area increases the runoff potential in the shallow subsurface layers. Therefore, infiltrated water from the top soil surface rapidly flows to downstream areas rather than recharging deep aquifers. For the same reason, Al-Khoud catchment area has small storage capacities (Z11, Z12 and Z2) than the Japanese catchments. Moreover the land-use types in the catchment area have a significant effect in retaining water in shallow subsurface layers. Absence of full grown trees with deep spread roots in Oman facilitates rapid subsurface flow which attenuates groundwater recharge and subsurface storage. This phenomenon replicate with small Z coefficients in Oman than in Japan. B1 coefficients between two catchments also depict significant differences. These variations indicate that the Al-Khoud catchment has higher infiltration capacity than the Japanese catchments, which may also be attributed to the low soil moisture content in Al-Khoud than in Japanese catchments.

V. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to develop a rainfall-runoff model to simulate Wadi flow in Muscat, Oman. Wadi Al-Khoud catchment area was selected. Model calibration was carried out with observations in 1997. The simulated Wadi flow model was verified with observation in 1997, 1999, 2000 and 2004. The Nash–Sutcliffe model efficiency coefficient of 0.88 could be obtained. The calibrated tank model parameters in Wadi Al-koud catchment area were compared with the parameters calibrated in several catchments in Japan. Physical meaning of the tank model parameters in arid environment could be successfully interpreted. It was found that the differences of model parameters of two catchment areas depend on vegetation cover, topography (RG) and soil moisture content.

The tank model performance highly depends on input data quality. Lack of long-term quality controlled rainfall and river discharge records was a major constrain. Respective authorities are therefore encouraged to maintain a long-term data base to facilitate academic community.

The results of this study showed the ability of the tank model to simulate Wadi flow with a reasonable accuracy and therefore will be applicable for climate impact predictions. In the next step of this study, downscaled GCMs scenarios from several models for different climate variables will be used with the developed tank model to simulate wadi flow variations in future.

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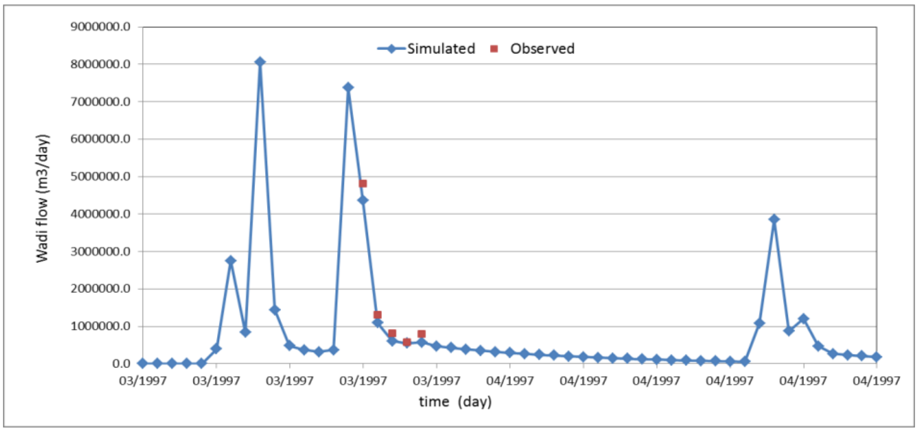

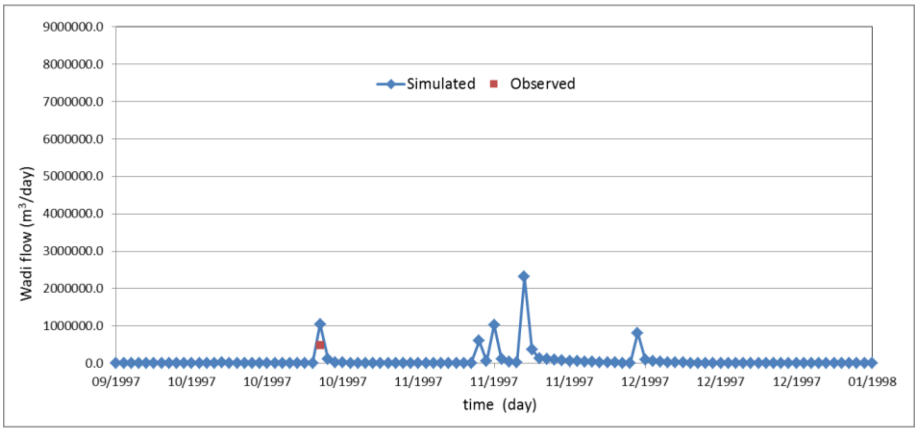

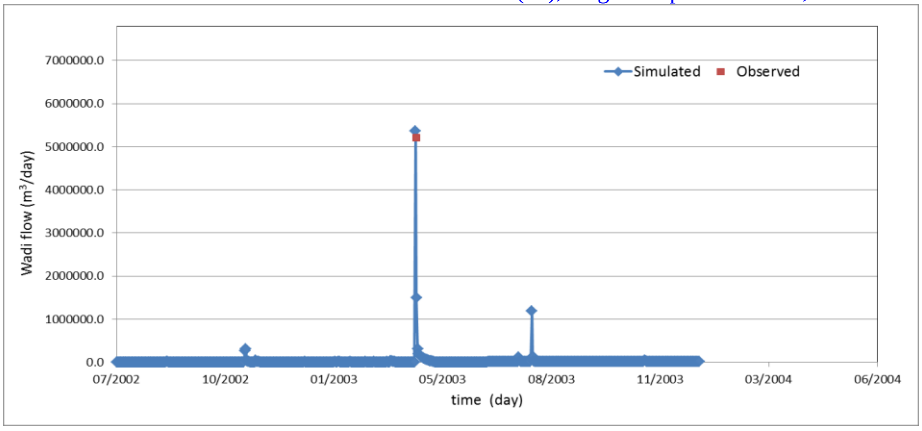

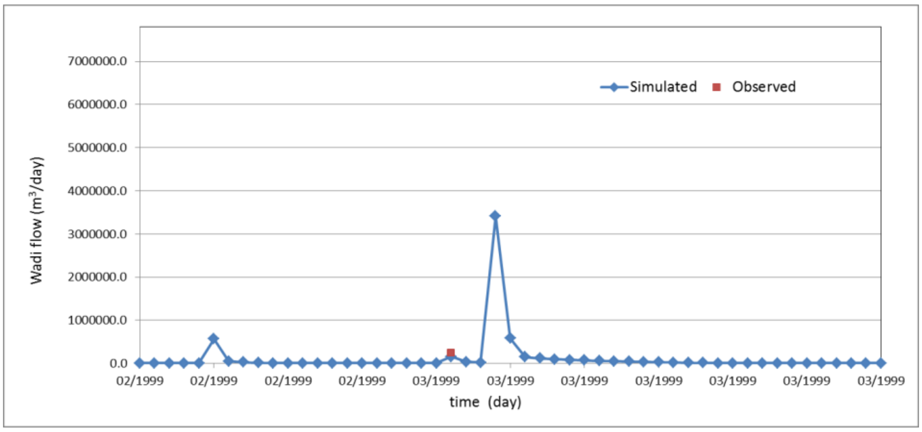

Fig. 3. Observed and simulated wadi flows