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Applying the Triangle Method for the parameterization of irrigated areas as input for spatially distributed hydrological modeling — Assessing future drought risk in the Gaza Strip (Palestine)

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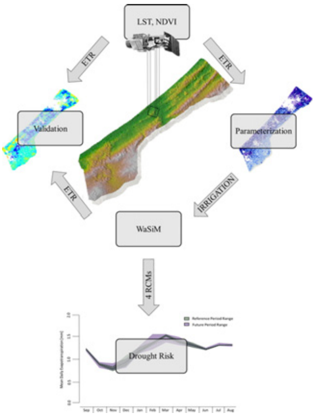
HIGHLIGHTS

- RCMs reveal increase in temperature & decrease in precipitation in the Mediterranean
- Climate change increases drought risk in the Gaza Strip
- Remotely sensed evapotranspiration used for parameterization and validation of WaSiM
- Future evapotranspiration index can be used as a robust indicator for drought risk
- Agricultural productivity cannot be maintained without adapting irrigation management

GRAPHICAL ABSTRACT



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ABSTRACT

In the Mediterranean region, particularly in the Gaza strip, an increased risk of drought is among the major concerns related to climate change. The impacts of climate change on water availability, drought risk and food security can be assessed by means of hydro-climatological modeling. However, the region is prone to severe observation data scarcity, which limits the potential for robust model parameterization, calibration and validation. In this study, the physically based, spatially distributed hydrological model WaSiM is parameterized and evaluated using satellite imagery to assess hydrological quantities. The Triangle Method estimates actual evapotranspiration (ETR) through the Normalized Difference Vegetation Index (NDVI) and land surface temperature (LST) provided by Landsat TM imagery. So-derived spatially distributed evapotranspiration is then used in two ways: first a subset of the imagery is used to parameterize the irrigation module of WaSiM and second, withheld scenes are applied to evaluate the performance of the hydrological model in the data scarce study area. The results show acceptable overall correlation with the validation scenes ($r = 0.53$) and an improvement over the usual irrigation parameterization scheme using land use information exclusively. This model setup is then applied for future drought risk assessment in the Gaza Strip using a small ensemble of four regional climate projections for the period 2041–2070. Hydrological modeling reveals an increased risk of drought, assessed with an evapotranspiration index, compared to the reference period 1971–2000. Current irrigation procedures cannot maintain the agricultural productivity under future conditions without adaptation.

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1. Introduction

According to current climate projections, the Mediterranean region will be affected by severe changes, both an increase in temperature as well as a decline in precipitation. The projections of climate models show a decline up to over 50% in the summer months, resulting in a rising frequency of drought events up to over 40% (Christensen et al., 2007).

Hydrological modeling can be applied to quantify these effects, provide decision support and develop effective water management strategies for the future. Usual procedures in hydrological model calibration range from the classical trial and error approach to sophisticated automized learning algorithms to fit a modeled output variable, typically discharge, to observations (Gupta et al., 1998). Statistical criteria, like the Root Mean Square Error or the Nash–Sutcliffe criterion (NSE) (Nash and Sutcliffe, 1970) are applied to validate the goodness of the model results. However, such approaches can be somewhat difficult for complex models or in heterogeneous catchments (Immerzeel and Droogers, 2008). Furthermore, if data for calibration and validation are scarce, this approach will add hardly quantifiable uncertainty to the results (Winsemius et al., 2009). The Predictions in Ungauged Basins (PUB) initiative (Sivapalan et al., 2003) increased the discussion on the work in ungauged basins (Winsemius et al., 2009). Possible solutions to calibrate a hydrological model in a data scarce area might be to apply the information of neighboring catchments as presented by Blöschl (2005), or to perform regional calibration by calibrating several catchments simultaneously (Parajka et al., 2007). However, both approaches imply knowledge of surrounding catchments, hence might not be applicable in many ungauged, data scarce areas.

Remotely sensed data can help find a solution to this problem as those data sets provide spatial information in an acceptable temporal resolution, which can be translated to hydrological variables. Schmugge et al. (2002) show general application of remote sensing to extract information on snow distribution, soil moisture and also water quality, Kite and Pietroniro (1996) provide an overview on this topic, Schultz (1993) used multispectral Landsat data to assimilate information for distributed hydrological modeling already two decades ago. Data assimilation for the parameterization and calibration of hydrological models is a more recent research field (Immerzeel and Droogers, 2008). Various studies assimilate remotely sensed soil moisture information in several hydrological applications (Boegh et al., 2004; Al-Shrafany et al., 2014).

Studies by Chen et al. (2005) and Immerzeel and Droogers (2008) focus on evapotranspiration, which tackles the traditional calculation of actual or real evapotranspiration (ETR) as an estimated fraction of potential evapotranspiration (ETpot) (Kite and Droogers, 2000). The latter compare evapotranspiration estimated from satellite information, hydrological models and field methods. Their results confirm the use of a remote sensing solution to estimate evapotranspiration, as the traditional field methods, FAO-27 and FAO-56 (Allen et al., 1998) showed ambiguous results. The two most widely used approaches to derive ETR from remote sensing are the Surface Energy Balance Algorithm for Land (SEBAL) and the Triangle Method.

SEBAL converts visible, near-infrared and thermal information to an estimate of evapotranspiration Bastiaansen et al. (1998a,b). The algorithm was applied for Landsat TM images by Kite and Droogers (2000), while Immerzeel and Droogers (2008) used MODIS information to derive evapotranspiration for the calibration of the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998).

In this study, another method to estimate evapotranspiration by remote sensing data is applied to parameterize the irrigation module hydrological model WaSiM (Schulla and Jasper, 2007) and to evaluate model performance. The Triangle Method, as presented by Price (1990), then established by Carlson et al. (1995) and Jiang and Islam (1999), was carried out for Landsat TM scenes to estimate the ETR for the Gaza strip. This method was chosen over SEBAL for reasons of required input data and will be briefly elaborated in Section 3. As water availability is the limiting factor for ETR, areas with high ETR during the dry summer months therefore have to be irrigated. Several of these Landsat TM scenes were then used to identify the irrigation areas and parameterize the model to distribute the amount of irrigated water over the catchment.

The objectives of this study are threefold: a) the Triangle Method was used to provide estimates of ETR to parameterize the irrigation module of WaSiM, as only irrigated areas show high evapotranspiration during the summer months. The procedure is presented in Section 3.3 and evaluated in Section 4.1; b) for lack of discharge data the performance of WaSiM will be assessed on the withheld scenes of the satellite derived evapotranspiration in Section 4.2; c) the WaSiM model setup is then driven with a small ensemble of regional climate model (RCM) simulations to assess future drought risk in the area as presented in Section 4.3. For a detailed analysis on the RCM-ensemble selection it is hereby referred to Deidda et al. (2013).

2. Study area

The Gaza Strip is located in the Eastern Mediterranean and forms, together with the West Bank, the Palestinian Autonomous Area, according to the Oslo agreement of 1993. The area covers 365 km^2 with a length of 35 km and width of 6 to 12 km (Baalousha, 2006). Sufficient supply of freshwater is a major concern for the rapidly growing population, which stands at approximately 1.5 million inhabitants and grew by 4.5% per year in the period 1997–2007. One third of the Gaza Strip is covered by urban or built up area, the largest city in the area being Gaza City with about 0.5 million inhabitants (Ajluni, 2010). Due to population growth, the total water demand in the Gaza Strip is strongly increasing. The current available resources do not satisfy the need of water, causing a huge deficit between water demand and supply (Qahman and Larabi, 2006).

Agriculture is the most important sector in terms of land cover, land use and water consumption in the Gaza Strip (Rusteberg et al., 2010). The main crops grown on the irrigated fields include tomatoes, potatoes, cucumbers, strawberries and melons. Furthermore, citrus plantations and olive orchards are widespread in the area. The climate conditions allow for more than one crop cultivation cycle per year.

The mean annual temperature for Gaza City is 20.1 °C and the mean annual precipitation 353 mm, resulting from events in the winter months, during the wet period October to April. The months May to September form the dry period, practically without any precipitation. A remarkable north-south gradient in precipitation is evident with 435 mm in the North, and 235 mm in the South as shown in Fig. 1. Differences in elevation are almost negligible as they range from sea level to 104 m. In the Gaza Strip no permanent surface water exists in form of streams and natural lakes. Only the Wadi Gaza could provide surface water during the winter months. The bed of the Wadi is characterized by a 1–2 m layer of unsorted Pleistocene gravel, originating from the mountainous areas in the Northern Negev and Hebron (MedWetCoast Project, 2001).

The major source of freshwater in the area is the coastal aquifer. This aquifer, hereafter referred as Gaza Aquifer, covers a large area of about 2000 km^2, from the Carmel Mountains in the North to the Sinai Desert in the South with a width of 15–30 km (Baalousha, 2008). The aquifer provides freshwater for the entire Gaza Strip, and parts of Israel, including the metropolis of Tel Aviv–Jaffa in the north. The depth of the aquifer varies from 170 m at the Mediterranean coastline to just a few meters in the eastern parts. Main components of the aquifer are alluvial sandstone, with local limestone and chalk areas, underlain by a massive, impermeable clay layer, the Saqiya formation, developed in the Pliocene era, with depths of 400 to 1000 m (Baalousha, 2006). Older groups, like the Judea, Kurnub and Arad Group contain dolomite and sandstone and developed between the Jurassic and Cretaceous era (Assaf et al., 1998).

As mentioned before, data scarcity is hampering the calibration and validation of the hydrological model. Fig. 1 shows the location of the twelve precipitation gauges available within the Gaza Strip. However,