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Using smart ICT to provide weather and water information to smallholders in Africa: The case of the Gash River Basin, Sudan

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A R T I C L E I N F O

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A B S T R A C T

In the Gash Delta of Eastern Sudan, spate irrigation (flood-recession farming) contributes substantially to rural livelihoods by providing better yields than rainfed dryland farming. However, spate irrigation farmers are challenged by the unpredictability of flooding. In recent decades, the number of farmers practicing spate irrigation has decreased, due to varying rainfall intensity and frequency, insufficient infrastructure and farmers' limited capacity to manage such variations. One solution that may help farmers face such challenges is for them to access real-time water-related information by using smart Information and Communication a Technology (ICT). This paper shows how integrating remote sensing, Geographical Information Systems (GIS), flood-forecasting models and communication platforms can, in near real time, alert smallholder farmers and relevant government departments about incoming floods, using the Gash basin of Sudan as an example. The Ministry of Water Resources of Sudan used the findings of this study to transform farmers' responses to flood arrival from being 'reactive', to planning for the flood event. Intensive on-site and institutional efforts to build the capacity of farmers, farmer organizations, development departments and officers of the Ministry helped to develop the initiative from simply sending 'emergency alerts' to enabling stakeholders to visually see the flood event unfolding in the region and to plan accordingly for storing water, operating spate-irrigation systems and undertaking cropping activities. The research, initially conducted on a 60 × 60 km site, was later extended to the entire Gash basin. The paper outlines how to develop tools that can monitor plot-specific information from satellite measurements, and supply detailed and specific information on crops, rather than providing very general statements on crop growth. Farmers are able to use such tools to optimize their farm profits by providing water to their crops in the right place, at the right time and in the right quantity. Finally, the work demonstrates the high potential of combining technology, namely remote sensing data and simple a agro-meteorological model with limited parameters, for large-scale monitoring of spate irrigation systems and information sharing to advise farmers as to how to apply this information to their managerial decisions.

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1. Introduction

Spate irrigation has been defined as a system that diverts flash floods from a riverbed via canals to bunded fields that may be located some distance from the water source (Lawrence and Van Steenbergen, 2005). The word "spate" refers to flood water originating from episodic rainfall in the upper part of river catchments, which, on arriving downstream, is diverted from ephemeral rivers and used to flood agricultural land. Spate water is often laden with eroded material and is thus rich in nutrients. In areas where rainfall is insufficient and no perennial rivers exist, spate irrigation systems can be a key element in the crop production needed to sustain livelihoods, providing an enhanced level of food security. According to Van Steenbergen and Mehari (2008), the global area under spate irrigation is approximately 2.6 million ha and an economically marginal population between 9 and 13 million are directly dependent on this system for irrigating crops. It is known to be widely practiced in West Asia (Pakistan, Iran, Afghanistan), the Middle East (Yemen, Saudi Arabia), North Africa (Morocco, Algeria, Tunisia), the Horn of Africa (Ethiopia, Eritrea, Sudan, Somalia) and East Africa (Kenya, Tanzania) (Mehari, 2007; Oudra, 2008; Van Steenbergen and Mehari, 2008; Komakech et al., 2011; Mehari et al., 2011; Steenbergen et al., 2011).

With increasing population pressure on land and water resources globally, the number of people dependent on spate irrigation is expected to increase. Despite being one of the oldest water-resource management systems, the technique is still poorly studied and insufficiently understood (Van Steenbergen, 1997; Mehari, 2007). However, in the last two decades, governments, non-government agencies and the donor community have increasingly recognized that spate irrigation is one of the main assets for improving the lives of poor communities (Tesfai and Stroosnijder, 2001; Steenbergen et al., 2010).

In order to benefit from spate irrigation, the general information needed includes: (i) timely forecasts detailing when and where floods may occur, and (ii) spatial monitoring of actual crop growth and moisture conditions. Forecasts guide farmers on when to prepare for irrigation, while monitoring crops and moisture enables them to act upon anticipated water stress and likely delays to harvesting. Spate irrigation areas are often difficult to access, which prevents information from being easily gathered on the ground. The resulting lack of knowledge on: the extent of flood waters in agriculture fields, the flooding from upstream to downstream and crop growth, along with the dearth of data products and ground observations, may affect crop yields and thus limit food security in rural communities. However, remote sensing (RS) from satellite data presents a range of opportunities for providing such information. Many examples exist of flood-inundation mapping from satellite-based sensors, such as MODerate resolution Imaging Spectroradiometer (MODIS) (Amarnath et al., 2012; Ogilvie et al., 2015). Similarly, satellites are already used to monitor crop growth and water consumption within agricultural fields (e.g. Pinter et al., 2003; Moran et al., 1997; Liaghat and Balasundram, 2010; Mulla, 2013). Today, a wide range of satellite data from coarser resolution (NASA MODIS, NOAA Suomi NPP) to medium resolution (USGS Landsat, ESA Sentinel-2) are available freely to generate end-user products from daily to the weekly basis to support plot-specific information concerning water and crops for agriculture management (Amarnath et al., 2017; Dinku et al., 2011; Ghebreamlak et al., 2018).

The study summarized in this paper examined the potential of RS technology to monitor crops and, flood forecasting to estimate flood flows in the catchment, where no such applications had been made before. The study also put into operation information systems for farmers and extension officers, which helped them to optimize farm profits and achieve "more crop per drop". It is expected that, in the future, the farmers will be able to increase their farm profits by directing the optimal volume of water to the right place, at the right time. The paper demonstrates the role of ICT systems for decision making through the use of web-based information and instant messaging (SMS/MMS) and thus aims to improve communication between farmers, water-user associations and higher-order public- and private-sector organizations. The effectiveness of this implementation is also discussed through an evaluation using sample surveys conducted among farmers.

2. Study area

The Gash River basin is a transboundary basin shared between Ethiopia, Eritrea and Sudan (Fig. 1). The river originates in the Eritrean Highlands and Ethiopian Plateau in an area characterized by steep slopes. Historically, the basin used to be part of the Nile River system (Elsheikh et al., 2009). The upper course of the river in Eritrea is known as the Mareb (Artan et al., 2007). It is an oasis in a surrounding desert with relative humidity ranging from 20 to 50%, annual rainfall from 180 to 280 mm (from Hadaliya to Kassala), and an average temperature from 26 °C in winter to 42 °C in summer (Bashier et al., 2014a). The topography of the basin varies from 53 to 3259 m above mean sea level. Located in the inland delta of the Gash River (15.46 N, 36.38 E), the Gash Spate Irrigation Scheme (GSIS) area is characterized by a semi-arid climate with two notable seasons: winter and summer. The area is one of the most important spate irrigation areas in Sudan. Population in the region is estimated at 87,000 households, of which 89% live below the poverty threshold (Bashier et al., 2014b). Spate irrigation has been practiced in this area for more than a century to produce the main crops, which include barley, cotton, and sorghum.

The Gash River, the water source of the (GSIS), travels 121 km from the border with Eritrea down to the Gash Die (end of the delta), with a net command area of 100,000 ha (Anderson, 2011; Ghebreamlak et al., 2018). As a seasonal river, it flows between late June and October, with high flows occurring between July and September. The maximum annual flow volume (1430 Mm^3) was recorded in 1983, while the annual minimum flow (140 Mm^3) on record occured in 1921 (Anderson, 2011). The average annual flow volume at El-Gera upstream gauge station and at Salam-Alikum downstream gauge station are 1056 Mm^3 and 587 Mm^3, respectively (Elsheikh et al., 2011).

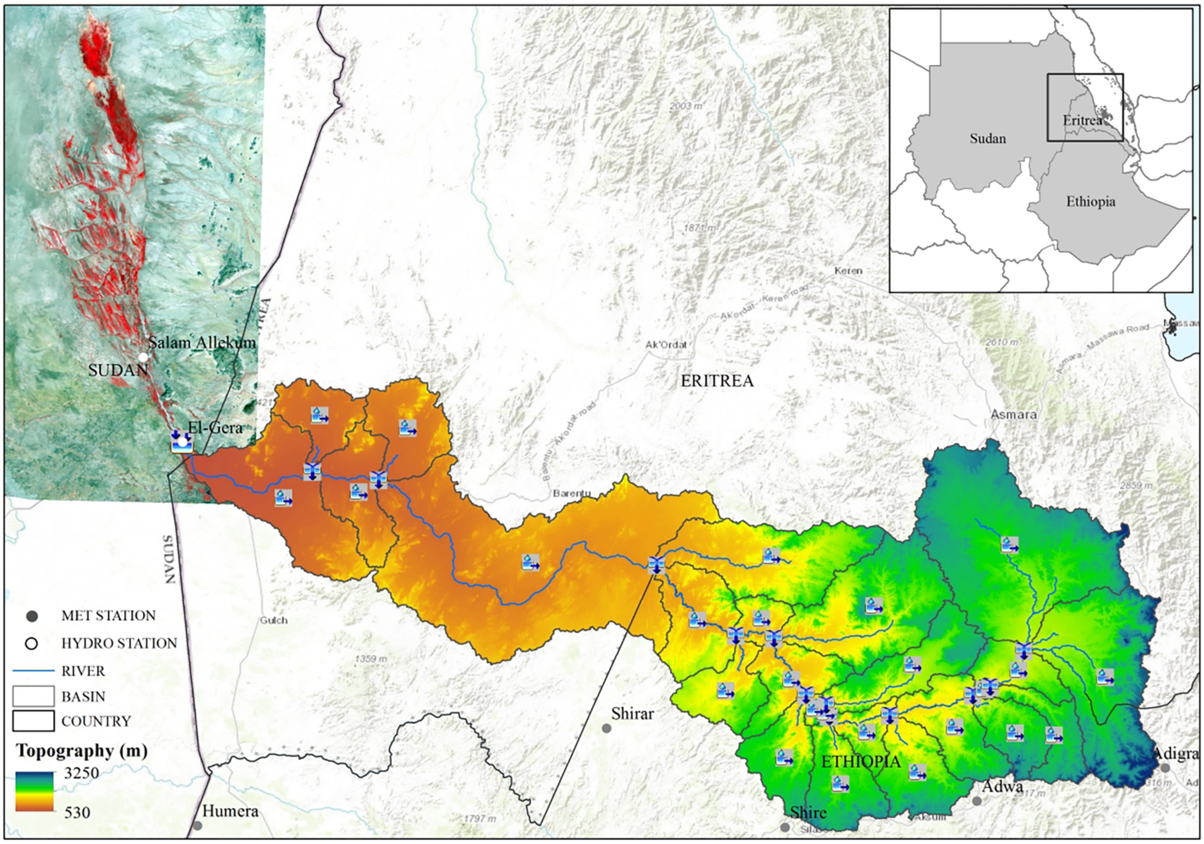

Fig. 1. Location map of the Gash River basin covering the countries of Ethiopia, Eritrea and Eastern Sudan. The hydrological modeling setup using HEC-GeoHMS model to estimate flood flows and USGS Landsat data of false color composite data for Gash Spate Irrigation Scheme (GSIS) showing details of healthy vegetation (red color) for the month of October 2012.

3. Data and methods

This section briefly describes four components of the research: (1) flood forecasting to estimate flood flows from upstream to downstream using satellite rainfall estimates and hydrological models; (2) monitoring crop growth and water consumption using a surface energy balance algorithm (SEBAL); and (3) sharing information with farmers through smart ICT using the FieldLook platform. The following individual sections collectively demonstrate how monitoring of spate irrigation and forecasting the floods, followed by disseminating information through ICT and collecting the feedback through sample surveys, assists farmers and local authorities to apply this information to their managerial decisions.

3.1. Flood forecasting system for Gash Basin

Hydraulic Engineering Center Geospatial Hydraulic Modeling Extension of the Center's HEC Hydrologic Modeling System (HEC-GeoHMS) software, which is an extension of Arc GIS, was used to derive the river network of the Gash basin, to delineate watershed boundaries, and to extract basin and river characteristics. The satellite-based precipitation data used in this study were obtained from the Tropical Rainfall Measuring Mission (TRMM), a joint project launched by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). The availability of the data in near real time has great potential for practical use in data-sparse and ungauged regions (Maswood and Hossain, 2016; Zambrano-Bigiarini et al., 2017).

Prior to using the satellite rainfall data, the bias correction factors obtained from the National Meteorology Agency in Ethiopia and Sudan were applied with a ratio of satellite and rain gauge data covering the study area with a total of 5 stations for the period 2007–2012. The objective of this study was to identify the historical floods using the hydrological model system (HEC-HMS) with the TRMM precipitation data. Evaporation has little effect on the simulation results, and flood events in the study area are primarily caused by extreme rainfall events; thus, local evaporation was neglected. The simulation strategies used in this study were The Soil Conservation Service (SCS) curve number (CN) precipitation-loss method, the SCS unit-hydrograph transform method and the Muskingum routing method. The base flow also takes into account the method of Constant Monthly. More details on the data used and the stepwise modeling procedure can be found in Amarnath et al. (2016).

3.2. Mapping inundated area in the Gash Spate Irrigation Scheme

To map inundation in the GSIS the study used two different satellite datasets: the MODIS/TERRA SURFACE REFLECTANCE 8-DAY L3 GLOBAL 500 M SIN GRID V005′ (MOD09A1), with an eight-day interval and a spatial resolution of 500 m, and USGS Landsat data with a spatial resolution of 30 m. A Modified Normalized Difference Water Index (MNDWI) and Normalized Different Vegetation Index (NDVI) proposed by Xu (2006) was adopted to identify the typical irrigated area.

3.3. Monitoring crop growth and water consumption

A combination of datasets obtained from the Disaster Monitoring Constellation (DMC www.dmcii.com/) satellites operated by Surrey Satellite Technology Ltd and the Visible Infrared Imaging Radiometer Suite (VIIRS http://www.nasa.gov/mission_pages/NPP/main/index.html) sensor on board of (NASA's) (www.earthobservatory.nasa.gov/) Suomi National Polar-orbiting Partnership (NPP) were used, on a weekly basis, to compute the parameters related to water consumption and crop growth. A satellite measures spectral radiance, which can be converted into components of the surface energy balance, including evapotranspiration, using RS algorithms. In this study, the Surface Energy Balance Algorithm for Land (SEBAL) algorithm was used to quantify heat and water-vapor exchange rates at the land-atmosphere interface (Bastiaanssen et al., 1998). In SEBAL, the instantaneous actual evapotranspiration (ET) flux is calculated for each cell of the remote sensing image as a "residual" of the surface energy budget equation:

$$ET = R_n - G - H \tag{1}$$

where ET is the latent heat flux (W/m^2), R_n is the net radiation flux at the surface (W/m^2), G is the soil heat flux (W/m^2), and H is the sensible heat flux to the air (W/m^2). The full theoretical and computational details of SEBAL are well documented (Bastiaanssen et al., 1998; Bastiaanssen, 2000; Bastiaanssen et al., 2005; Teixeira et al., 2008).

Biomass production was calculated according to the principles of the ecological production model of Monteith (1972). This model is based on total active photosynthetically absorbed radiation (APAR) and a value for light-use efficiency (ε) that converts the radiation absorbed into dry matter production (kg/ha). The duration of sunshine is used to compute global radiation on a day-to-day basis. The interception of this radiation by biologically active canopies is derived from the vegetation index. The light-use efficiency is approximated as a maximum value for C3 crops and a reduction factor depending on the opening of the stomata behaviour of the leaf-level carbon and water exchange to maximize net canopy photosynthesis (Danielle et al., 2014).

In this study, SEBAL was applied weekly for the Gash Delta during the July-December cropping seasons in 2012 and 2013, with the spatial resolution of the model runs chosen in accordance with the high-resolution DMC data (20 m). DMC satellite radiances were converted first into land surface characteristics, such as surface albedo and the Normalized Difference Vegetation Index (NDVI, which is a measure of plant vigor). As DMC does not measure the thermal part of the electromagnetic spectrum, surface temperature was acquired from the NPP VIIRS data. No additional information on soil type, crop type or hydrological conditions was required to apply SEBAL. Auxiliary inputs consisted of a digital elevation model (obtained from the NASA Shuttle Radar Topography Mission [SRTM]) and a basic satellite-derived land use map, discriminating between water, vegetated areas, bare soil and built-up areas. The SEBAL model also requires routine weather data: wind speed, relative humidity and air temperature. We obtained these data from Kassala meteorological station (15.46 N, 36.38 E) for use in the SEBAL model. Following the guidelines of the United Nation's Food and Agriculture Organization (FAO) (Allen et al., 1998), reference evapotranspiration (ET_{ref}) was inferred from weather data and atmospheric transmissivity (Fig. 2).

In addition to providing high-resolution spatial biomass data related to crops, an irrigation decision support system (IDSS) can help farmers to optimize their irrigation scheduling and avoid oxygen and water stress to crops (provided that water availability at the inlet is not the limiting factor). By combining satellite data showing vegetation cover/surface albedo and SEBAL-calculated evapotranspiration with weather forecasts, it is possible to predict the soil water balance in the root zone for 5 days to allow for precise predictions of crop water requirements with unprecedented spatial resolution. (Johnson and Trout, 2012; Pelosi et al., 2016; Calera et al., 2017). Based on these principles, the IrriLook model (Bastiaanssen et al., 2009) was used to solve the soil water balance for the forthcoming 5 days and to identify possible occurrences of stress. Insufficient available water in the root zone leads to suboptimal crop development, while irrigation applied above soil field capacity – and therefore redundant – leads to percolation and results in the loss of irrigation water at the farm level. In addition to satellite information and the IrriLook model, the IDSS requires ongoing interaction with farmers or extension officers. Soil properties, crop type and groundwater conditions per field need to be communicated at the start of the season and irrigation applications need to be reported. The full extent of the Gash Delta was covered by DMC images during the cropping seasons of 2012 and 2013. Field sizes were sufficiently large for limiting the impact of mixed pixels on field-scale mapping. As Landsat 8 became available over the course of 2013, these images were also included in the system to enhance the crop monitoring. Parameters that were monitored are listed in Table 1.

3.4. Data delivery to farmers through smart ICT

The FieldLook platform (Bastiaanssen et al., 2009) was selected as an appropriate tool for disseminating the field-specific results of the satellite-based analyses to farmers in the GSIS. Operational services based on FieldLook have been successfully applied for many years in countries around the world, for example in Russia (www.fieldlook.ru) and South Africa (www.fruitlook.co.za). A successful FieldLook system has also been operational for the Gezira Scheme in Sudan since 2015 (www.fieldlook.com.sd). During 2012 and 2013, all farmers, agricultural extension officers, research staff and other stakeholders in the Gash Delta had the

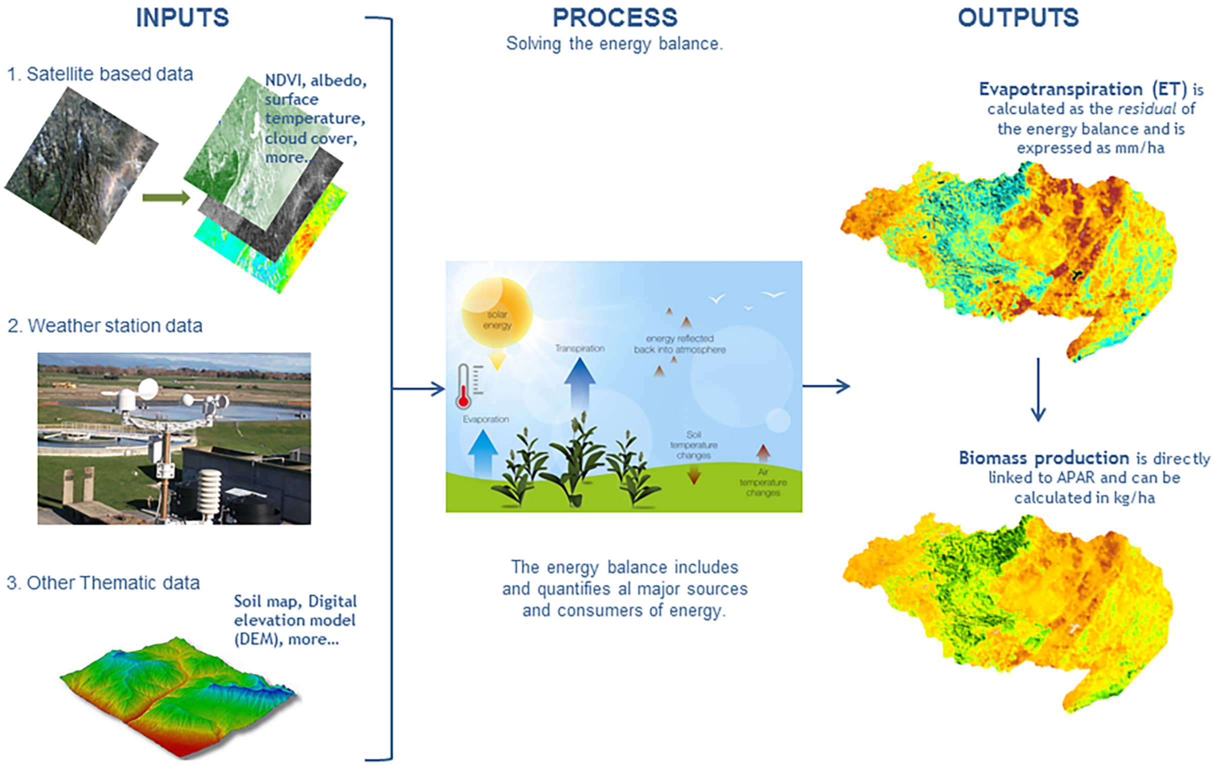

Fig. 2. SEBAL workflow for computing evapotranspiration and biomass consumption (Source: eLEAF Competence Center).

Table 1
List of weekly output maps (20 × 20 m resolution) related to crop monitoring. LAI and NDVI are instantaneous observations, available from the moment the satellite image is captured.

Parameter	Details
Actual evapotranspiration [mm]	Total amount of water consumed during a certain week
Evapotranspiration deficit [mm]	The number of millimetres of water per week the crop below that needed to achieve the maximum evapotranspiration (and growth). It is a direct indication of plant water stress
Biomass Water Use Efficiency [kg/m^3]	The amount of dry matter that is produced per cubic meter of water consumed.
Biomass production [kg/ha]	The amount of dry matter that grows each week. This includes the harvestable part of the crop and other biomass such as, leaves, stem, and weeds.
Leaf Area Index (LAI) [m^2/m^2]	The total live canopy leaf surface area of vegetation divided by the surface area of the land on which the vegetation grows. LAI is an indicator of the amount of leaf surface as well as how densely a crop grows, or how much foliage there is on the plants.
Vegetation Index (NDVI) [−1 to +1]	Indicates the vitality of a crop. A high index means healthy and vigorous vegetation.
Crop Factor [K_cK_s]	This is used to calculate the actual evapotranspiration from the reference evapotranspiration. It incorporates the effect of a specific crop (K_c) as well as the effect of water stress (K_s) on the water consumption of that crop.

opportunity to register via a web portal to access a pilot system providing data on their respective fields (see Table 1 for an overview of data layers). Some 60 smallholder farmers received extensive support to access and interpret the data delivered for their specific blocks. The selected plots were growing sorghum (75%), fruits (9%), vegetables (9%) and mixed vegetables and fruits (7%). Relevant data layers were extracted weekly from the spatial database for the entire Gash area. In practice, the spatial data in FieldLook (Fig. 3) was primarily accessed by extension advisors, due to smallholder farmers lacking access to the internet. Extension advisors used this service to identify weakly performing fields, or zones within a field, and communicated any anomalies to the farmer. They were also able to access an IDSS, which provided information on field-specific conditions and direct advice on when to irrigate each field, given the weather forecast.

Although the use of a web portal proved very useful for visualizing and communicating agricultural information, and also in offering interactive options, it was not accessible to the majority of the smallholder farmers directly. With most farmers lacking access to the internet, the web portal service was complemented by SMS to send timely agricultural information and irrigation advice to the farmers themselves. The SMS service was designed to summarize spatial information in a short message in the most meaningful way to the farmer, based on the outcomes of user consultations during several workshops. Information on biomass production and water-use efficiency was extracted from the database and messages were sent out weekly to individual farmers. They were also provided

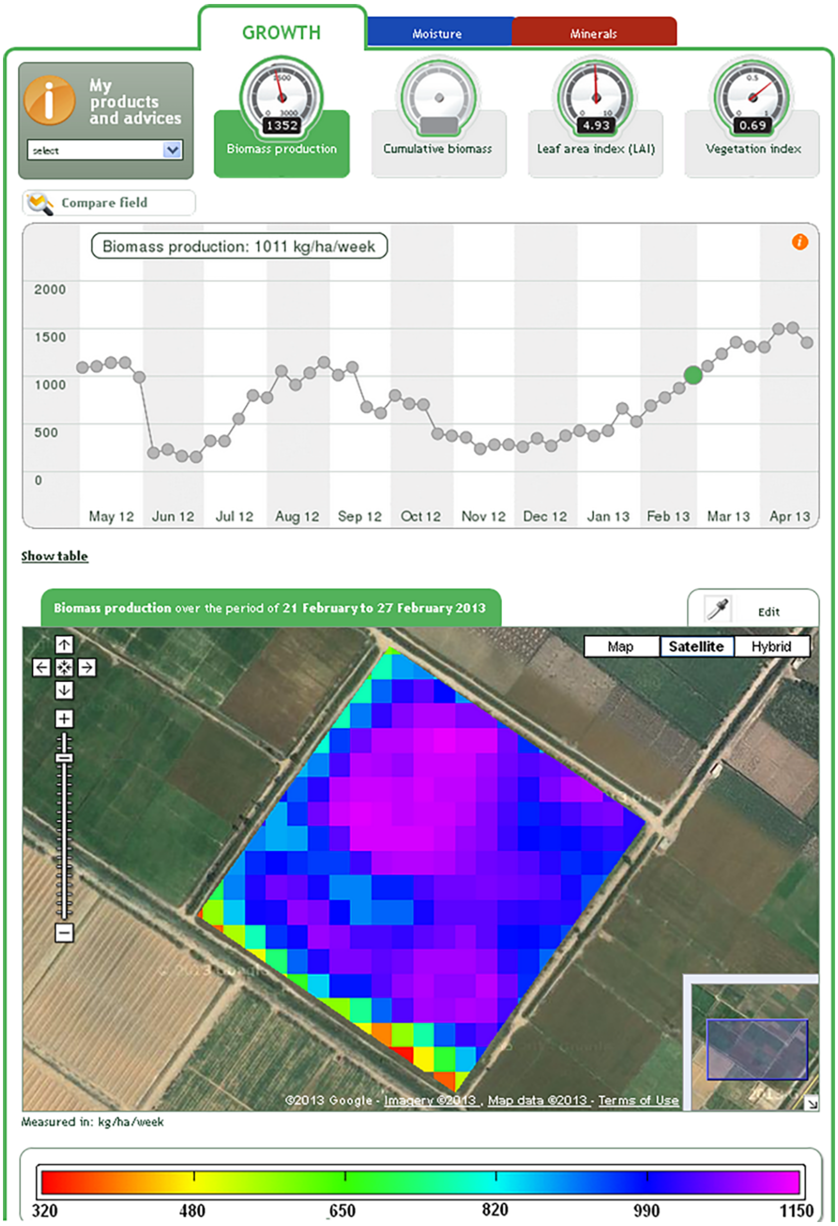

Fig. 3. Screenshot of the FieldLook web page for an individual field with a time line of crop biomass production (top) and a map of intra-field variability in biomass production for the selected week. All values are in kg/ha/week.

with qualitative information indicating whether their crop performance was higher, lower or similar in relation to that of other farmers growing the same crop during the same week in the growing season.

The SMS service enabled farmers to access the IDSS by sending information requests and receiving advice in response by mobile phone. Farmers were advised on the right time to irrigate: immediately, in 1–2 days, 3–4 days or not at all within the next 5 days. In this manner, the IDSS helped farmers to prevent their crops from experiencing water stress and thus maintain an optimal level of crop production. This component of the SMS did not consist of "push" messages sent out to the farmers but was activated upon specific requests from individual farmers by SMS (Fig. 4). These requests were formulated from single characters to minimize the number of incorrectly typed requests. In the same way, farmers were able provide qualitative indications of irrigation applications (full/medium/low) to the system by means of single-character SMS messages. At the end of the spate irrigation season, the study conducted an individual beneficiary survey among various stakeholders on the overall usability and application of the SMS system.

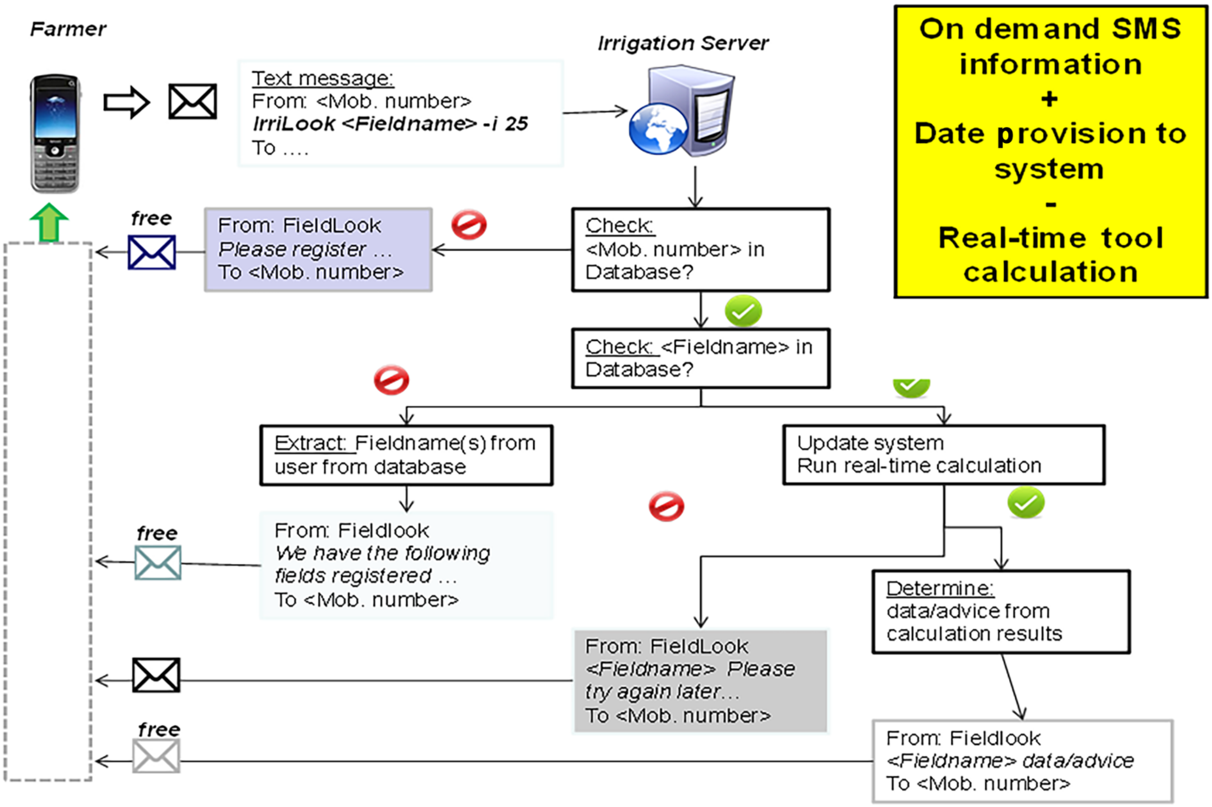

Fig. 4. Illustration of the set-up of the on-demand IDSS component of the SMS system for Sudan. A farmer sends the request for a specific field/crop, the IrriLook model is run based on the most recent weather forecast and tailor-made irrigation advice is computed and delivered instantly to the farmer.

4. Results and discussion

4.1. Mapping surface water extent in the spate irrigation scheme

The extent and distribution of floodwaters varied considerably in the GSIS between 2012 and 2014. The variation in the extent of inundation during June to September 2013 for the Gash scheme is shown in Fig. 5. The peak of inundation, revealed by MODIS/Terra satellite images, occurred in August. A closer view of flooded areas, from Landsat images, for the Degain and Tendelai blocks pinpointed the period of maximum inundation to between 8^{th} August and 1^{st} September 2013.

Fig. 6 shows the temporal distribution of inundated areas for the entire GSIS, which range from 400 to 600 Km^2) out of the total geographical study area of 2020 km^2. The average inundated area equates to approximately 30% of the total area. The scheme has experienced serious deterioration; as frequent drought spells have led to increased pressure on the already meagre water resource. There has also been an invasion of mesquite trees, and irrigation waters have become laden with sediment in many blocks. These factors have led to an acceleration of degradation in the study area (Nzumira, 2014; Zenebe et al., 2015).

The Makali, Degain and Tendelai blocks were inundated most of the time during the high flood phase, with water levels increasing dramatically at the start of the period. As observed in Fig. 5, the inundation mapped from Landsat images for the Degain block was higher in the average flood phase with a continuing decrease through to the dry flood phase and the high flood phase. The maps and flood information were disseminated to the relevant agencies and individual farmers using the FieldLook portal and SMS.

4.2. Flood forecasting and providing early warnings

Prior to using NASA TRMM rainfall estimates to compute the hydrograph, these data were validated with rainfall station data from the Ethiopia National Meteorology Agency. Rain gauge observations from five stations were obtained for bias correction, adjusted to satellite rainfall estimates (SRE) and subsequently integrated into the hydrological model. The computed discharge (during the hydrograph validation stage) and actual observations of discharge from the Kassala Bridge station are shown in Fig. 7. This figure indicates that the computed hydrographs match well with the observed hydrographs. Real-time flood forecasting was provided by continuous simulation of flood hydrographs using the 3-hourly NASA TRMM SRE data during the 2013 flood season (Fig. 8).

Table 2 presents Nash Sutcliffe Efficiency (NSE) and relative volume error (RVE) for three different years during the calibration

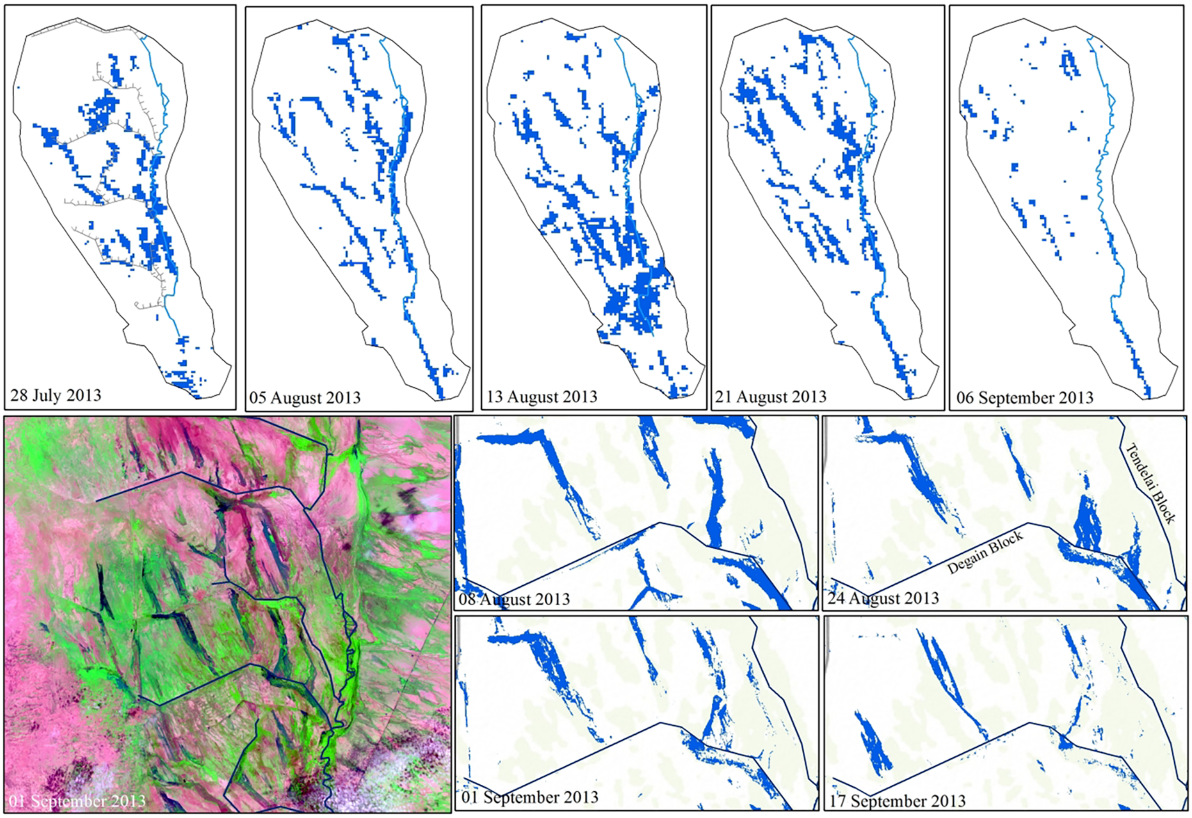

Fig. 5. Spatial and temporal distribution of irrigated area mapped between July 2013 and September 2013. The top image shows irrigated fields obtained using MODIS Terra data, the bottom images were obtained using USGS Landsat data.

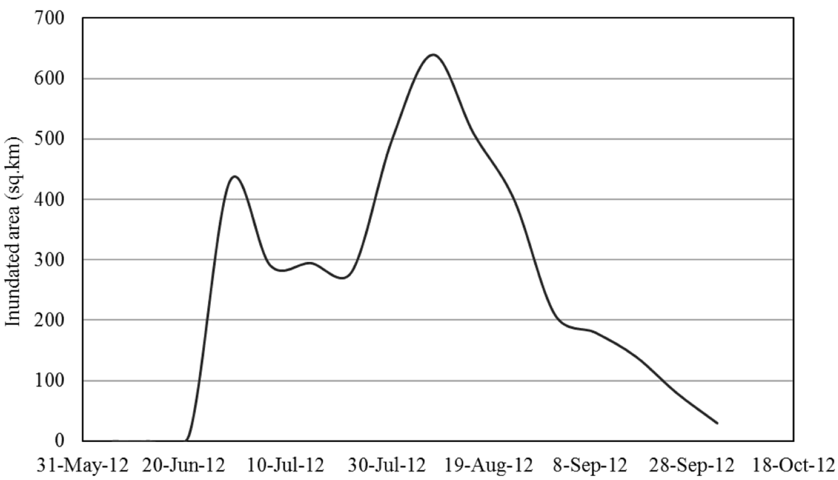

Fig. 6. Seasonal distribution of the extent of surface water across the Gash River catchment between June and September 2012 based on MODIS Terra time-series datasets.

and validation periods in the Gash catchment. The model shows that during the calibration period RVE is very small, indicating that the average simulated and observed discharges are close to each other. General testing of conceptual models (Rango, 1992) has shown that an NSE value higher than 0.8 is above average for runoff modeling. Therefore, NSE values obtained during calibration are satisfactory for the Gash catchment; the highest value (0.79), was achieved by the 2011 flood season. During the calibration period, the peak values are generally underestimated but discharge during periods of low flow is well simulated by the HEC-HMS model. During the calibration period, efficiency (Y) values and hydrograph showed that performance of the 2011 model is satisfactory.

During validation, RVE values agreed reasonably well with the calibration phase. Evaluation of the model performance in terms of

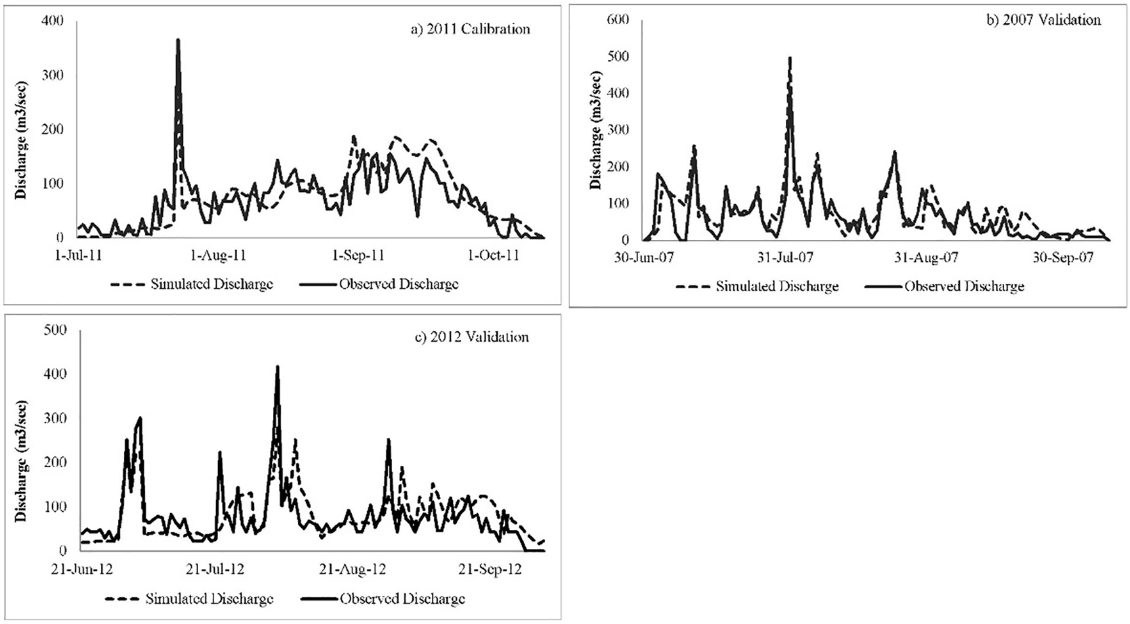

Fig. 7. Observed and simulated discharge (m^3/sec) for the Kassala Bridge station during the (a) 2011 calibration, and the 2007 (b) and 2012 (c) validation periods.

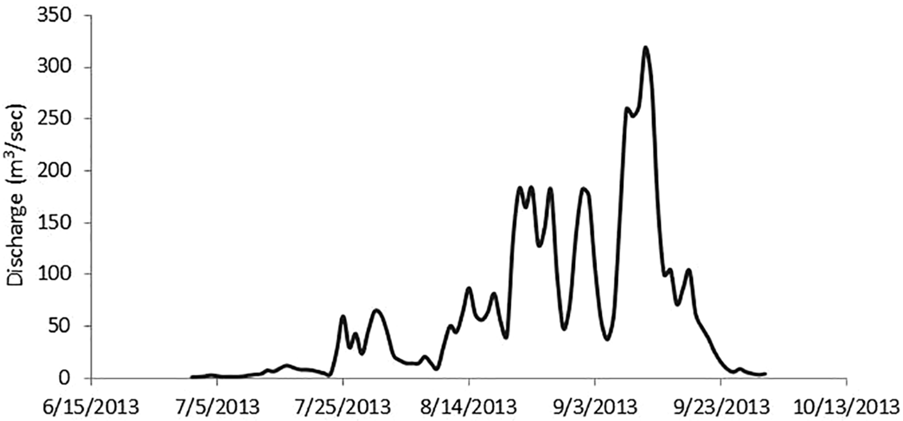

Fig. 8. Near real-time simulated flood hydrographs at Kassala Bridge for the 2013 flood season.

Table 2
Model calibration and validation for the Kassala Bridge Station, Gash River basin.

		NSE	RVE (%)
Calibration	2011	0.79	−0.05
Validation	2007	0.72	−0.17
	2012	0.71	−0.06

the objective functions also shows very good model performance in line with our visual inspection. The RVE is very small (−0.17%), suggesting very good model performance in terms of capturing observed stream flow volume. The model performance is fair in reproducing the pattern of the observed hydrograph (NSE = 0.7). We note that flood discharges commonly are difficult to observe since discharges often are based on stage-discharge rating curves that generally become inaccurate for higher river water levels. We can see that the discharge during the 2006 extreme year and was not captured well by the model. This could be due to changes in the rainfall-runoff relationship, by discharge observation errors or an inaccurate rating curve during periods of riverbanks overflow during a flood event. Overall, the values of the objective functions provide an aggregated assessment of model performance.

Table 3
GSIS flood classification.

Flood	Irrigated Area (%)
Good	60+
Normal	35–60
Bad	up to 35

The model could forecast most of the flood peaks exactly. Accuracy in computing peak discharge during the flood events was 79% when compared to the observed flows. Model computations were 13% higher than the observed discharges. This error could be due to several factors, including upstream abstraction and losses due to evapotranspiration or groundwater recharge, which the model could not take into account. Flood forecasting lead time is increased by 12 h compared to conventional methods. This will help in forecasting flood discharges at intermediate river junctions. Discharge in any sub-basin of the study area could be predicted by adopting this approach.

In the Gash Delta, floods used for irrigation are categorized by farmers as good, normal or bad according to the area irrigated (Table 3; information obtained from discussions with farmers from three different canals at Fota, Salam Aleykum and Makali main canals, which comprise the Kassala and Makali blocks). As can be seen from Figs. 6 and 7, the Gash River flows continuously during the irrigation season, but with fluctuations in the discharges. Besides the flow regime, each intake regulates the water that can enter into the canal and there is a defined irrigation duration for each intake.

Most other spate systems define floods differently than the GSIS. According to Mehari 2008, in Wadi Laba spate, Eritrea, floods are defined by the number that occur, with a minimum of 9 floods for a dry year. Floods are categorized by 6 classes, with medium floods discharging from 25 to 50 $m^3 s^{-1}$ and occurring annually while a very large flood, discharging from 200 to 265 $m^3 s^{-1}$ occurs at least once every 3 years. The same classification system is applied in spate systems in Ethiopia, Pakistan, Yemen and in the Toker scheme in Sudan (Zenebe et al., 2015). By comparison, the GSIS flood classification is related to the flooded area and its impact on crop yield.

In most spate systems, a field water layer is observed during the application time, which defines the duration of application. However, in GSIS this does not occur in the same manner; the applied depth cannot be seen as a surface water layer. Instead, the duration of the field water application is set for durations varying from 15 to 30 days (Zenebe et al., 2015).

The GSIS spate has two important features, as defined by FAO Spate guidelines. These features are 1) the diversion of water using wadi channels via canals to irrigate bounded fields located far from the intake, and 2) the size of the GSIS being such that the farmers work as a group to divert and distribute flood waters and to maintain their intakes and canals (Mehari Haile et al., 2010). In addition, a central authority manages the use of water across the scheme.

Despite the importance of flood-recession farming to these communities, this farming system presents many challenges, such as unreliability in the timing of floods, labour shortages and agricultural policies that do not favour spate-irrigation farmers. Variability in the extent of flooding is the most important factor in determining the extent to which GSIS farming is practiced (Nzumira, 2014; Lee et al., 2015). The majority of the interviewed stakeholders agreed that a Flood Early Warning System (FEWS) for the river is of great importance (Fig. 9). Setting up a FEWS can save farmers' lives and properties and help to avoid damage to crops. Such a system can also help in harnessing the floodwater by enabling farmers to decide on how best to divert water via canals based on the flood magnitude. Of the interviewed stakeholders, 78% believed that having flood information could help reduce labour efforts.

4.3. Monitoring of crop growth and water consumption

Fig. 10 gives an impression of daily SEBAL outputs that were computed for the capture dates of the satellite images. The figure shows the relation between satellite reflectance, evapotranspiration and biomass production. It is clear that the 20 m resolution is sufficient for extension officers and farmers to observe spatial differences between fields, and also to a certain extent within fields. Spatial variation in water consumption and biomass production can be caused by a variety of factors, including crop variety, sowing

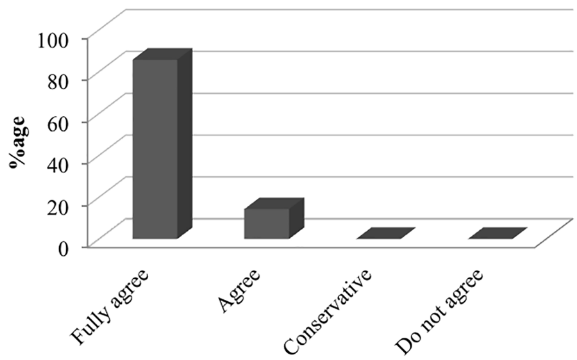

Fig. 9. Importance of FEWS in the Gash River basin.

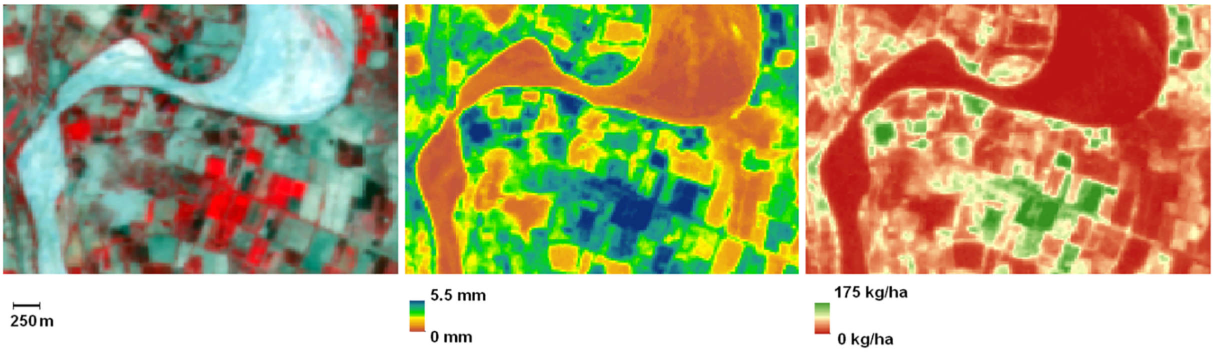

Fig. 10. Raw DMC satellite data for 21-11-2012 (left image), derived daily evapotranspiration (middle image) and biomass production (right image).

dates, water supply, fertilizer application, soil type and the occurrence of diseases.

Due to the scarcity of observed data and remoteness of the region, it was a challenge to evaluate the quality of the different data layers that were delivered to the farmers. The quality of the satellite imagery over the Gash basin was found to be generally good, with over 70% of the satellite images captured being largely or completely cloud-free, thereby enhancing opportunities for quantifying the parameters listed in Table 1. However, actual evapotranspiration (ETa) is a difficult parameter to measure on the ground, and no field measurements were available from the study area. Although it is therefore not possible to directly validate our estimates of water consumption of agricultural fields in the GSIS, the SEBAL methodology is a proven methodology in areas around the world, with ETa errors generally lower than 5% (Karimi and Bastiaanssen, 2014).

Fig. 11 presents the cumulative biomass production of 10 sorghum farmers in the GSIS during the 2013 flood season. Although the temporal pattern is similar among the farmers, it is clear that conditions and/or agricultural practices during the season were more favorable for some fields than others. For example, farmer MH achieved total biomass production of over 16,000 kg/ha, while farmer MM only achieved around 5000 kg/ha.

At the end of the 2013 spate irrigation season, the service provided through the smart ICT project was evaluated by: 1) completing a questionnaire with the individual beneficiary farmers; 2) holding an open discussion with government stakeholders; and 3) making in-depth analyses at field level. The analyses were undertaken to derive quantitative data on seasonal values for parameters related to growth, moisture, minerals and floods.

For a single crop, cumulative biomass production should be strongly correlated to crop yield (Burke and Lobell, 2017). Farmers in the GSIS record their crop yield by the number of sacks, with one sack corresponding to 100 kg. Fig. 12 shows the relationship between field data on crop yield and satellite-derived estimates of biomass production. The R^2 value of 0.752 indicates that there is a strong correlation between biomass production calculated from RS and that provided by farmers' observed crop yields, which puts strong confidence in the biomass production data delivered to extension officers and farmers. In other words, satellite-derived biomass production succeeds in providing a spatial diagnosis of crop health in the GSIS and enables extension officers and farmers to identify strongly and weakly performing areas. Correlations between biomass production and crop yield can therefore be used to make informed decisions on food security prior to harvesting.

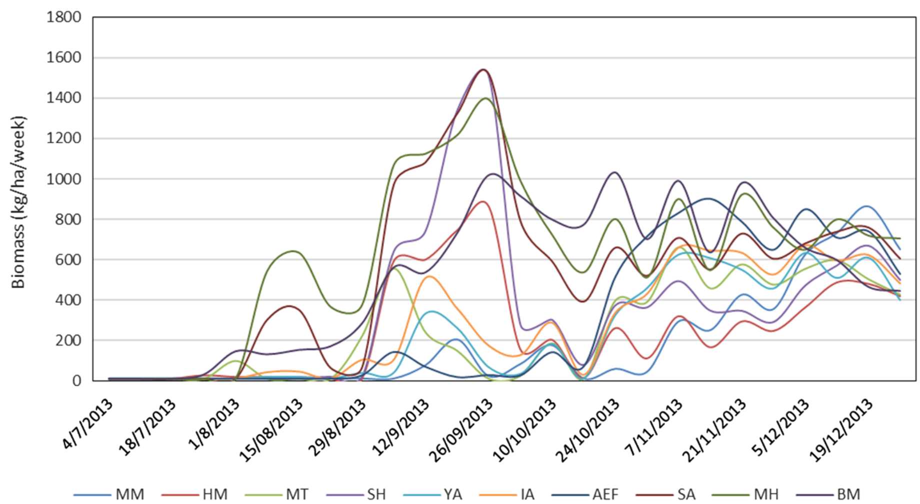

Fig. 11. Cumulative biomass production during the 2013 growing season for 10 sorghum farmers in the Gash Spate Irrigation Scheme (GSIS).

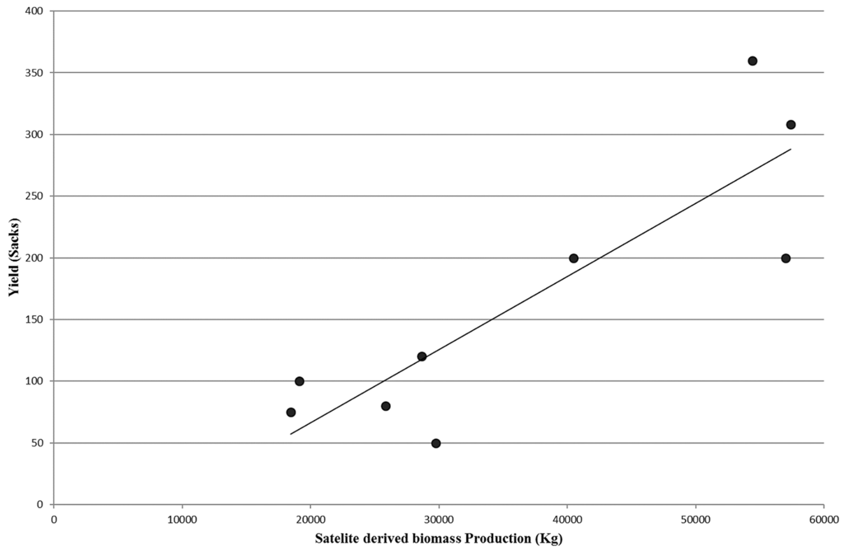

Fig. 12. Validation of biomass production with crop yield for 10 sorghum farmers in GSIS.

A number of case studies that interpret on-farm management practices and/or active the use of advisory services incorporate hi-tech information. For example, information collected on growth parameters and inundation days for 2012 was used to advise farmer AAF on the suitability of his field's soil for cultivating Aklamoy. Aklamoy is variety of sorghum that has a growing season of 120 days. The farmer suspected that the soil in his field was not good and could not hold enough water for cultivating Aklamoy; instead, he was growing the Tabat variety, which requires only 40 days to grow. During the 2013 season, on our advice, AAF cultivated his field with Aklamoy and Tabat varieties, achieving 31 sacks/ha for Aklamoy. Information extracted from the FieldLook website showed that the average NDVI for the 4-month growing season was 0.43, indicating a healthy and strongly growing sorghum. For the whole season, the evaporation deficit fluctuated around an average of 5.25 mm/week. This means that the crop never experienced water stress (Fig. 13).

Inundation maps are very useful for the Gash basin and can significantly contribute to Gash floodwater management when provided at the scale of individual farms. Knowing the exact inundation periods will help farmers to select the appropriate crop type for each inundated field. In the above example, AAF's field was inundated for approximately 17 days and the crop did not experience water stress. This means that 30 days of inundation wastes about 70% of the floodwater, when the flooded area is used for sorghum cultivation.

Of all the information delivered, irrigation advice from the IrriLook model relies the most strongly on dynamic information provided by extension officers and farmers themselves, in particular the times and amounts of irrigation. The quality of irrigation

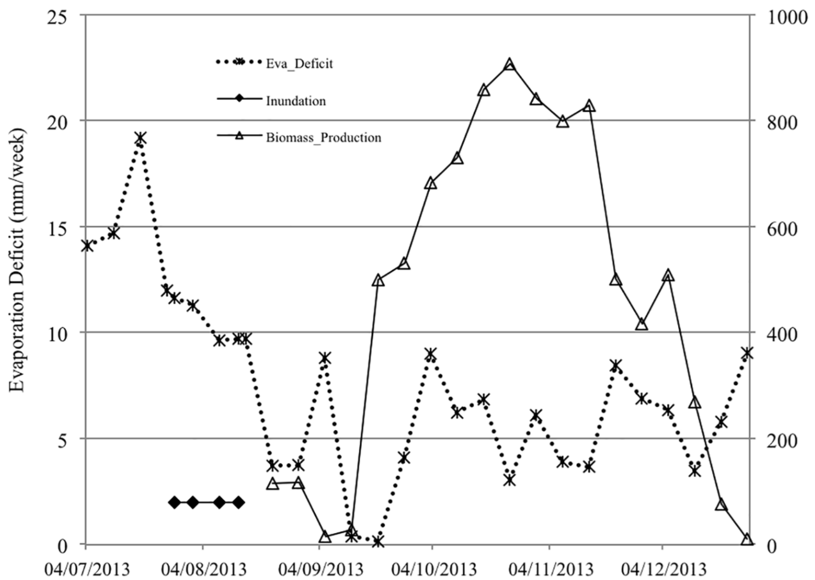

Fig. 13. Information for AAF's field showing flood inundation duration, evapotranspiration (ET) deficit and biomass production.

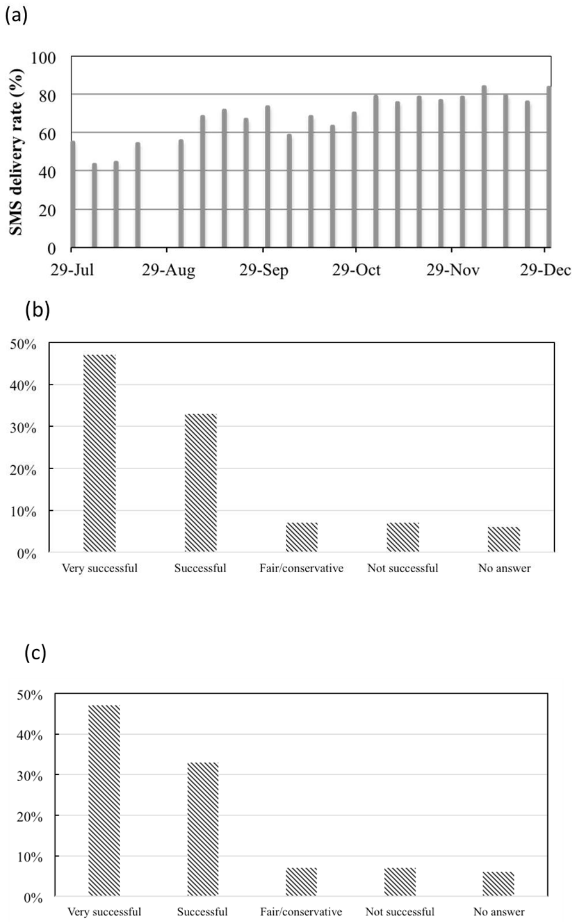

Fig. 14. Benefits obtained by farmers using smart ICT in the GSIS.

advice could theoretically be further improved by providing more accurate, quantitative irrigation amounts to the system rather than qualitative indications; however, the exact volume of applied water is generally unknown to the farmers (Jones et al., 2000; Hirschberg et al., 2011; Kox and Thieken, 2017).

Some fruit farmers used the irrigation advice they received to reduce their pumping costs. For example, farmer MK turned off his pumps whenever he received an irrigation message saying “no need to irrigate”. Similarly, MA used spate irrigation to inundate his sorghum field once. He requested irrigation advice many times during the growing season and he always received a message telling him that there was “no need to irrigate”. He concluded that the inundation of his farm was sufficient and his crop never suffered from a water shortage during its growth season.

4.4. Delivering smart ICT data to farmers to inform decision making

Factors influencing the success rate of SMS delivery were found to include the anticipation of messages by farmers (thus making sure their phones were accessible) and the reliability of the network signal. After initial start-up issues, extensive guidance was provided to the farmers to ensure successful SMS delivery. The delivery success rate increased from around 50% to 80% during the 2013 growing season (Fig. 14).

Of all information requests submitted by the farmers via SMS, 51.4% concerned requests for irrigation advice and 48.6% concerned information from the FieldLook platform (biomass production and water productivity). Irrigation advice was mainly requested by farmers with access to groundwater through wells, as these farmers had the most control over when to supply water to their crops and how much to apply.

5. Conclusions

Spate irrigation is becoming more important in areas experiencing climate variability, where it can contribute significantly to local and regional food security – and in a world of higher food prices and reduced food aid assumes greater importance. This paper describes the potential of RS and modeling tools for providing timely forecasts detailing when and where floods may occur, spatial monitoring of actual crop growth and moisture conditions and disseminating information via smart ICT throughout the growing season to help farmers to take the best actions to safeguard their crops.

Remote sensing can easily provide information on spatial variation within fields, but such nuances are lost in a text-based SMS. Therefore, intensive support from extension staff in analyzing the spatial maps and communicating effectively with illiterate farmers remains very important (Feldman and Ingram, 2009). The study carried out user feedback to evaluate the performance of the research framework and explore how farmers wish to receive advice. Advice, rather than information, is more likely to lead to behavioural changes and should therefore be the focus of any follow-up smart ICT tools.

The greatest impact of smart ICT services is expected in areas where farmer's actions are currently the primary limitations to production and thus farmer income. Selecting areas to implement these services should therefore be undertaken according to this criterion; a leap in production should be possible when farmer behaviour changes while other boundary conditions remain the same (Lemos et al., 2012). Cooperation with the local water user associations and irrigation water distribution boards and flood management units will lead to more meaningful irrigation advice, as well as a reduced flood risk downstream. Planned water availability at the gates of individual farms should ideally be incorporated in irrigation advice provided through the web and SMS system. Currently, irrigation advice is mainly provided based on desired schedules of irrigation. Irrigation amounts are not provided, as this is not a meaningful measurement to the smallholder farmer. Advice could possibly be provided in terms of the opening of the water inlets (e.g. frequency, timing and duration) at the block or even field level.

When the purpose of using smart ICT methods is to save water and improve water use, it requires fine-tuning by water boards and belief on the part of the farmers that water schedules will be available as planned. Otherwise, farmers will prefer to apply more water than necessary whenever they have water to avoid the risk of delay in the next water provision. The pilot areas have proven to be suitable areas for implementing RS-based technologies, as weather conditions in these areas allowed for 70% of the image acquisitions to be of good quality. This increased the quality of the data products and the derived farm-management advice. Validating data in these areas is a challenge, however; while ET is hard to measure, SEBAL is a proven methodology with a deviation of ~5% based on many scientific studies. The linkage between actual yields and computed biomass production should be further investigated to improve the advice provided and move forward from providing information on biomass production to forecasting yields.

Improvements to water availability cannot be isolated from improvements across the entire farming system. A technological advance in one aspect (e.g. water) without similar improvement in other aspects (e.g. soil tillage, use of improved varieties, nutrition management and pest and disease management) will have little impact on crop yields and be economically inefficient. In conclusion, the scaling up of weather and climate information and related advisory services for smallholder farmers are critical and are enabled by institutional arrangements and investments in capacity building that support sustained interaction between climate forecasters, agricultural organizations and farms as well as facilitate the dissemination of climate information to a climate service in the GSIS. In addition, climate services must be delivered at a local scale to be relevant to farm decision making. Finally, a seamless suite of forecast, advisory and early warning products at a range of lead times enables farmers to manage evolving risks throughout the growing season.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data for this article can be found online at https://doi.org/10.1016/j.crm.2018.10.001.

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