Validation of soil moisture derived from water balance method and satellite observation

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ABSTRACT. Under the present study estimation of high resolution soil moisture (SM) under Pan India mode using simple water balance method and from satellite data has been explored. It aims at the simple calculation of soil moisture followed by verification with ground truth data of SM on spatial and temporal scale (WC) as climatic input. The model has been verified for winter (January-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-December) seasons of year 2013. The comparison of model estimates with the in-situ data from 17 ground stations (for 396 paired datasets) over different seasons produced a better correlation coefficient varying from 0.46 to 0.60. The spatial comparison of SM estimated from model and satellite SM for the monsoon season shows a greater degree of coherence over most parts of India. Model derived weekly gridded SM combined with higher resolution satellite SM could be used to calculate the soil moisture requirements for the proposed block level agromet advisory services.

Key words – Soil water balance, Agromet advisories, Microwave soil moisture, GIS.

1. Introduction

Soil moisture is an important hydrological variable for climatic and agricultural modeling. It plays a critical role in governing water and energy balance between the land and atmosphere (Elfati, 1998; Brubaker and Entekhabi, 1996; Brocca et al., 2011). It is an important factor in crop water stress monitoring, water management studies and also as input data in various crop simulation and yield prediction models. The extreme events of floods and droughts are also strongly modulated by the soil moisture state of the landscape (Mohanty and Skaggs, 2001). The regular and national scale agro-meteorological monitoring requires retrieval or estimation land surface variables such as soil moisture to derive crop condition indicators to advise farming community on agricultural
TABLE 1
Selected ground observation stations for SWB model validation

| Station                   | Soil texture | Climatic zones     |
|---------------------------|--------------|--------------------|
| Agra (27.10° E 78.05° N)  | Sandy loam   | Semi-arid          |
| Basti (26.48° E 82.46° N) | Loam         | Dry sub-humid      |
| Bikaner (28.10° E 72.55° N)| Sand         | Arid               |
| Jammu (32.88° E 74.84° N)| Sandy loam   | Dry sub-humid      |
| Kalyani (22.57° E 88.20° N)| Silty clay  | Moist sub-humid    |
| Nagpur (21.06° E 79.06° N)| Clay loam    | Dry sub-humid      |
| Niphad (20.06° E 74.07° N)| Clay loam    | Semi-arid          |
| Sabour (25.14° E 87.04° N)| Clay loam    | Dry sub-humid      |
| Sagar (23.51° E 78.45° N)| Clay loam    | Dry sub-humid      |
| Udaipur (24.35° E 73.42° N)| Sandy loam  | Semi-arid          |
| Ludhiana (30.56° E 75.52° N)| Sandy loam  | Semi-arid          |
| Solapur (17.67° E 75.90° N)| Clay loam   | Semi-arid          |
| Pune (18.53° E 73.85° N)  | Clay loam    | Dry sub-humid      |
| Bellary (15.15° E 76.85° N)| Clay loam   | Semi-arid          |
| Thrissur (10.31° E 76.13° N)| Sandy loam  | Humid              |
| Hissar (29.17° E 75.77° N)| Loam         | Semi-arid          |
| Karnal (29.72° E 76.97° N)| Loam         | Dry sub-humid      |

operations and management. The SWB and water balance indices at a given location provides useful information on soil moisture storage, the period of water deficit and water surplus (Shweta and Krishna, 2014). The estimates of SWB are used for estimating probable length of growing season, irrigation needs (Droogers et al., 2010), leaching of soils for salts (Maas and Hoffman, 1977), fluctuations in water table, drought hazards and soil water availability in different regions and for judging the agricultural potential of the region. The quantitative results obtained also can be utilized for agro meteorological applications.

A large part of India lies in the arid and semi-arid tract, where irrigation sources are limited; agricultural in these areas depends mainly on the distribution of rainfall. Erratic distribution of rainfall in these regions draws special attention to plan different strategies of crop production using stored water in the soil profile. Research studies to calculate soil moisture using soil water balance method, and its application to agriculture as well as hydrology have been carried previously by Adhikari et al., 2004; Allen et al., 1998; Ghadekar, 2003; Mehta et al., 2006; Pascua, 2000; Sontakke et al., 2008. In these studies, soil water balance parameters have been computed mostly on monthly basis for limited number of stations. From the agricultural point of view, information of soil moisture on weekly basis, on a spatial scale would be highly useful to the scientific community, planners and other users. The weekly soil moisture data can also be utilized to plan suitable time of sowing of both kharif and rabi crops. The accurate spatial and temporal distribution of soil water content is essential in hydrology, climate and soil-vegetation interaction processes. The available SMs the upper layers of the soil are of much importance for crop sowing and crop health during the crop growing period. Site specific water content cannot be applicable over a regional scale (Westenbroek et al., 2010). The soil water content calculated in gridded format using simple GIS data layers and climatological data layers are useful for regional studies. The development of such simple gridded soil water content information is extremely helpful to the proposed project Gramin Krishi Mausam Sewa (GKMS) launched by India Meteorological Department (IMD), Ministry of Earth Sciences (MoES) in the country under the 12th Five Year Plan to provide additional input for framing for the block level agromet advisory. The use of the modelled SM is to be verified for the use of agromet Advisories. In future the model and satellite SM product would be combined together for the proposed block level agromet advisory services. The
objectives of this study are (i) To generate the weekly gridded maps of SM using water balance model over India (ii) its validation using the \textit{in-situ} observations from soil moisture network stations and (iii) Spatial comparison of model and satellite SM

2. Study area and data used

2.1. Study area

Different agricultural regions spread over India were selected for \textit{in-situ} soil moisture measurements to validate SWB moisture content estimates. The lists of these regions and their coordinates, as well as climatic characteristics are given in Table 1. The regions represent a wide variety of soil types. Observations in \textit{rabi}, \textit{kharif} and dry (bare soil) season were taken at these ground stations. At some of these stations, Cotton is generally is grown as a rainfed crop in India. The other crops taken in the monsoon season (\textit{kharif}) are rice, maze and gram. \textit{Rabi} groundnut is grown in residual soil moisture conditions. The other \textit{rabi} crops like wheat, mustard and gram are taken in post monsoon and winter seasons.

2.2. \textit{In-situ data}

2.2.1. Soil moisture content (SM)

The list of stations from which \textit{in-situ} soil moisture data observations used in this study are presented in Table 1. In India, there is a network of 42 soil moisture observatories which are collecting the soil moisture data. A quality check of the data was performed for each available station. Out of the 42 stations 17 available stations with different climatic conditions, cropping patterns and soil types were selected for this study.
The gravimetric method, also called the thermostat-weight technique (Robock et al., 2000), is used to measure soil moisture at these stations. Gravimetric methods of soil moisture estimation are the most widely used techniques and also consider standard for calibration of all other soil moisture determination techniques.

2.2.2. Gridded rainfall

The gridded rainfall data are being produced daily over India at a grid resolution of $0.25^\circ \times 0.25^\circ$ through Shepard interpolation of measured rainfall from 6955 rain-gauge stations distributed over India (Rajeevan et al., 2006; Pai et al., 2013). The daily gridded rainfall data for 2013 are available from National Climate Centre (NCC), IMD Pune. The average weekly gridded data from daily files is computed for further analysis.

2.2.3. Potential evapotranspiration (PET)

Meteorological data on maximum and minimum temperature, morning and afternoon relative humidity, wind speed and bright sunshine hours for the
period (1971-2005) have been utilized from well
distributed 144 locations in India for estimation of
Potential Evapotranspiration (PET) by Penman-Monteith
equation (Allen, 1998). Data of weekly PET have been
utilized as input for computing weekly climatic SWB. The
station wise climatological PET data for 144 stations were
used from published work of IMD (2008).

2.3. Satellite data

2.3.1. AMSR-2 soil moisture

The Advanced Microwave Scanning Radiometer 2
(AMSR-2) is a passive microwave sensor on-board the
Japan Aerospace Exploration Agency (JAXA's) Global
Change Observation Mission 1-Water (GCOM-W1)
satellite launched in May 2012. It is the successor of the
first passive microwave sensor, Advanced Microwave
Scanning Radiometer for the Earth Observing System
(AMSR-E) used widely for soil moisture retrieval (Koike
et al., 2004; Njoku et al., 2003; Paloscia et al., 2006). The
surface soil moisture for the year 2013 from AMSR-2 is
acquired from GCOM-W1 site (https://gcom-w1.jaxa.jp).
The surface soil moisture content from AMSR-2 at
25 km × 0.25° is used for further spatial validation of the
model SM.

3. Methodology

3.1. Spatial interpolation of PET and FC

PET and FC data from 144 stations were stored as
point data in the GIS software. These point information
were interpolated to prepare spatial raster layers of PET
and FC. The interpolation technique provides values for
any location in the region of interest. The kriging
technique is adopted for creating the raster layers from
point data in ArcGIS software. The grid size for both the
layers was given to be 0.25° × 0.25° corresponding to the
gridded rainfall grid size. The spatial layer was projected
to Geographic Lat./Long., WGS 84 projection. These
weekly generated spatial layers of PET and FC were
further used as inputs in the SWB model.

3.2. Soil water balance model (SWB)

The Soil water balance equation is used to determine
the water stress or excess water content in the soil. A
simple soil water balance has been computed weekly by
water budgeting procedure based on the method of
Thornthwaite and Mather (1955). The model is mentioned
as simple as it requires knowledge of just three variables,
field capacity (FC), rainfall (RF) and potential
evapotranspiration (PET). The water budget components
are calculated by comparing values for RF and PET. The
actual soil moisture (SM) was calculated using following
two equations:

(i) When RF exceeds PET

\[ SM = RF - PET \]  \hspace{1cm} (1)

(ii) When PET exceeds RF

\[ SM = (FC) \times \left(\frac{Acc(RF-PET)}{FC}\right) \]  \hspace{1cm} (2)

Acc. (P- PET) is the accumulated potential water loss. FC is the field capacity per meter depth of soil.

The station wise PET was converted to a raster layer in GIS using simple interpolation method. The raster layer
was prepared with same sample size of the gridded rainfall. The FC varies according to the soil type and soil
texture at the given place. The soil texture at each PET
station and ground observation station of SM was studied.
Accordingly the raster layer of FC was generated. These
raster layers along with the gridded rainfall were
incorporated in equation 1 and 2 and SM content was
calculated using GIS environment. The weekly spatial
maps of average SM were generated for all the standard
52 weeks of 2013. The gravimetric data from the ground
observations was converted to volumetric measurements
using equation 3 to compare with the model SM.

\[ SM_v = SM_g \times \frac{\rho_b}{\rho_w} \]  \hspace{1cm} (3)

where, \( SM_v \) is volumetric SM and \( SM_g \) is ground
observation data. \( \rho_b \) is the soil bulk density (g dry soil per
\( cm^3 \) soil) and \( \rho_w \) is density of water (1 g water per \( cm^3 \)
water).

In this study, the AMSR-2 soil moisture content,
representative of a layer depth of ~ 5-10 cm is spatially
compared spatial outputs of model SM. Pearson
correlation coefficient, bias and root mean square
deviation (RMSD) were used to compare the molded and
in-situ SM. RMSD was used to underline that ground
measurements may also contain errors (instrumental and
representativeness) and, hence, they cannot be considered
as the “true” SM.

4. Results and discussion

The modelled SM for all the seasons is compared
with observed \( SM_v \). A total of 396 paired datasets of
observed and modelled SM over all the four seasons at
available ground stations are compared. The modelled and
TABLE 2
Error analysis of modeled and observed soil water content

| Season        | n  | RMSD  | % MAD  |
|---------------|----|-------|--------|
| Winter        | 90 | 21.31 | -12.93 |
| Pre-Monsoon   | 90 | 30.09 | -22.69 |
| Monsoon       | 120| 20.83 | -3.15  |
| Post-Monsoon  | 96 | 23.89 | -9.57  |

observed $SM_v$ were categorized in winter, pre-monsoon, monsoon and post-monsoon season. The Figs. 1(a-d) represents the seasonal scatters of SM. In the winter season better correlation ($r = 0.60$) is observed between the modelled and in-situ data. In the pre-monsoon season the model estimated marginally larger SM as compared to the ground observation. The model did not perform well in the pre-monsoon (dry) season presenting a low correlation coefficient of 0.46. The scatter plot of monsoon and post monsoon seasons show a correlation coefficient $r = 0.60$ and $r = 0.59$ respectively. RMSD and MAD were calculated to compare the modeled and in-situ SM. The least RMSD of 20.83% with MAD of -3.15% was observed for monsoon season and maximum RMSD of 30.09% with MAD of -22.69% was in pre-monsoon season (Table 2).

The difference in the model and observed $SM_v$ can be attributed to the difference in the spatial coverage. The gridded rainfall data also fails to show spatial variability as compared to the observed data. Moreover the static PET values used in the model along with generalized raster layer of FC can also lead to the error gap between modelled and observed $SM_v$. The irregularity of the ground observation data is also a general problem of the validation study.

In the present study spatial comparison of modeled SM with AMSR-2 satellite SM is performed for the monsoon season starting from first week of June (Standard week no. 23) to last week of September (Standard Week no. 40). The spatial variation in the both the SM content for the monsoon season is given in Fig. 2. The maps are categorized in to 4 classes depending on the available SM, very low (< 0.1), low (0.1-0.2), moderate (0.2-0.3) and high (> 0.3). The increasing SM area with the advancement of the monsoon season is clearly seen for the modeled and satellite outputs. The model shows higher range of SM in the standard weeks from 32 to 39. The North western part and Southern part of India shows a very low and low SM in both the outputs. The model SM shows a limited variation as compared to satellite SM. The model is not able to detect the higher (>0.3) and lower (<0.1) range of SM. The use of common FC and saturation of PET and gridded rainfall values may have limited the SM variation in the model. However the model SM matches with the satellite SM over most part of India except area with higher satellite SM in the gangetic plains. The overall spatial pattern of low and moderate SM matches in both the outputs over the western, eastern and central region of India. The limited station PET and FC data over the northern hilly and eastern coastal region could be one of the reasons for the model to fail in these regions. Further analysis is required to improve the model SM. The AMSR-2 SM shows better spatial variation than the modeled SM. AMSR-2 SM needs to be further validated with the in-situ data from more stations, over different seasons for confirmation on the usability for agromet advisory services. Also the approach of integration of the modeled and satellite data can be established for the further improvement in estimated SM.

5. Conclusions

The simple SWB model described above can prove to be a useful tool to calculate the available water content on a regional scale for agro-climatological analysis. The attempt made to use a simple agro meteorological model may not be a very accurate tool to calculate the different components of the crop water balance. However, the model can be used to give an idea on a regional scale to monitor the soil water budget and to provide agromet advisories for irrigation scheduling on a broad range. This simple model approach can be operationally implementable to generate weekly SM at regional-scale. However, some uncertainties in this model approach have been identified. The model is unable to distinguish between bare (uncovered) soil surface and vegetation. It distinguishes five soil texture classes, but does not differentiate between salt-affected soils and others.
model gives no information on the runoff of the water surplus. In spite of these weaknesses, the present model makes possible the overall spatial estimation of SM. The use of static PET instead of near-real time PET and the limited number of PET stations in the northern hilly and eastern coastal region for preparation of raster layer could also be the possible reasons of the uncertainties. With the increased number of ground station network and ground truth data the results can be improved. At present agromet advisories are provided on district level. The integration of the high resolution satellite SM with the modelled SM can improve the outputs for block level agromet advisories. This integrated gridded information generated on country-wide SM status on a weekly basis will be helpful for planning and policy making related to agriculture and water resource development. Further scope of the study is the use of satellite data inputs in the SWB model to improve the results. The AMSR-2 and SMOS SM will be further integrated with the model SM to improve the results to provide high resolution outputs for block level advisories.

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