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# Conceptual development of a spatially distributed water budget model and application in Indian Watersheds

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***Abstract***: *In the era of freshwater scarcity, it is important to have a detailed knowledge about the status of available water resources and its pattern of use in different sectors. Assessment of water balance can be used as an important tool for decision-making in water resources planning and management. But, poor availability of hydro-meteorological data (especially, the data on evapotranspiration, solar radiation, infiltration etc. on daily time step at local scale), often, limits application of several established water balance models, such as, SWAT,* ANSWERS, *WBM, MIKE SHE, etc. In this context, this paper proposes a conceptual framework of a newly developed GIS coupled, spatially distributed water budget model named as SVWBM (Spatial Variation in Water Budget Model) considering the limitation of publicly available data in India. The model can be applied in both gauged and ungauged catchments at any desired time scale. It would assist the process of linking land use planning with water resources planning and management to ensure wise-use of water at watershed level. A framework of model development describing its components, steps of operation, advantages and limitations is presented, here.*

***Keywords:*** *Water budget, Spatially distributed model, Freshwater scarcity, Land use planning, Water resource management.*

## 1. Introduction:

To our great concern, decreasing availability of freshwater is now a worldwide phenomenon. Water scarcity may be ‘real’ which is climate-driven or may be ‘apparent’ while it is human-induced [36]. In order to exercise control over the human induced scarcity, land use planning needs to be sensitive to the water balance scenario which calls for integrated water resources management [37, 41]. And, to perform the whole process, it is important to have a detailed knowledge about the status of available water resources and its pattern of use at regional and/or local scale, at a seasonal basis, since, estimation of water balance in long term (annual measurement), may underestimate the status of water stress condition of a region [35, 3]. Assessment of water balance thus can be used as an important tool for decision-making in water resources management [2, 7].

### 1.1. Review of existing models:

In the Indian conditions, availability of data is a concern for researchers and planners for assessing the water balance. Only few watersheds are gauged and availability of ancillary data for hydrological modeling is not available in same temporal and spatial scale. Therefore six desirable criteria for any hydrological model to suit conditions existing in the study area considered are -

1. the model should be distributed monthly or seasonally, water-scale model;
2. the model must be capable of calculating watershed water budget, both for gauged and ungauged catchments;
3. the model must be successfully applicable for plain land topography;
4. the model should have relatively low data requirement;
5. the model should include human water use for different activities as an output component in water balance computation; and,
6. the model can be combined with GIS and is simple in application and GUI driven

Some of the established hydrological models were reviewed in context of the above mentioned six criteria. Limitations in applicability of these models are listed in Table 1.

***Table 1:*** *List of widely used Hydrological Models applicable in water balance assessments*

| ***Model*** | ***Application*** | ***Author(s)*** | ***Conformity with desirable criteria*** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** |
| **CREAMS** | A Field-scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems.<br>Estimate pollutant loadings. | Knisel, [55]<br>Foster et al., [21]<br>Lane and Ferreira, [32]<br>Jamieson and Clausen, [8]<br>Knisel & Douglas-Mankin, [56] | Lumped | Gauged | √ | Moderate | X | √ |
| **AGNPS** | Agricultural Non-Point Source Pollution Model<br>Simulate runoff, erosion and sediment, nitrogen, phosphorus, COD from agricultural watersheds | Young et al. [47]<br>Grunwald & Leon and Lam, [33]<br>Finn et al. [39] | Distributed | Gauged | √ | Very High | X | √ |
| **HSPF** | Hydrological Simulation Program-FORTRAN model<br>Simulate the hydrology, erosion, sediment transport, nutrient and pesticide movement, salts, dissolved oxygen, from both urban and rural areas. | Johanson et al. [48]<br>Johnson et al. [4]<br>Skahill, [5] | Semi-distributed | Gauged | √ | High | X | √<br>F<br>O<br>R<br>T<br>R<br>A<br>N |
| **SWAT** | Soil and Water Assessment Tool<br>Simulate runoff, sediment generation, nutrient movement | Arnold et al., [29]<br>Kaur et al. [46]<br>Pikounis et al. [38]<br>Fohrer and Arnold, [42]<br>Chekol et al. [17]<br>Ndomba et al. [45]<br>Gitau & Chaubey, [40] | Distributed | Gauged and Non-gauged | √ | Moderate | X | √ |
| **SWIM** | Soil and Water Integrated Model | Krysanova et al., [54]<br>Krysanova et al., [19] | Distributed | Gauged | √ | Very High | X | √<br>G<br>R<br>A<br>S<br>S |
| **MIKE SHE** | Simulates hydrological and water quality processes on a basin scale. | DHI, [18]<br>Demetriou & Punthakey, [14] | Distributed | Gauged and non-gauged | √ | High | X | √ |
| **WASMOD** | WAter and Snow balance MODeling system<br>Water balance at small to medium sized catchments<br>Simulating hydrological impact on climate change | Xu et al., [12]<br>Xu, [11]<br>Müller-Wohlfeil et al., [15]<br>Engeland et al., [30] | Lumped | Gauged and non-gauged | √ | Low | X | √ |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **WBM-QUALHYMO** | Water Balance Model powered by QUALity HYdrologic Model Principal focus is on source controls for runoff reduction, besides, water quality control, rainwater storage routing, etc. | Dr. Charles Rowney (developer), 1980s XCG Consultants, 2008 | Continuous simulation modelling tool | Gauged | √ | High | X | √ |
| **SWBM** | Spatial Water Budget Model<br><br>Simulates water supply and demand over space and time on a daily basis<br><br>Delineates streams and computes availability of stream water as it flows down slope or is extracted by human beings | Luijten, J. C., [27]<br>Luijten et al., [26]<br>Luijten et al., [25]<br>Luijten et al., [24] | Distributed | Gauged | √ | Low | √ | √ |

The hydrological models studied are complex, data demanding, incapable of estimating watershed water balance in ungauged watersheds and do not include quantity of human water use as output component in water budget computation. Of all the models only, the Spatial Water Budget Model (SWBM) developed by Joseph Carlos Luijten in 1999 [27]matches with the requirements, although, significant changes are necessary to assess the status of water balance of a catchment, either gauged or ungauged, at any temporal or spatial scale, with very low data requirement.

Therefore this research aims to develop a methodological framework of assessing the status of water balance in a watershed which would cater to the earlier mentioned objectives.

## 2. Methodological framework of Spatial Variation in Water Budget Model (SVWBM):

SVWBM is a distributed parameter, watershed scale model that can simulate water budget of both gauged and ungauged catchments at any desired temporal scale using raster GIS data structures. SVWBM is a tool for assessing the degree and intensity of potential water scarcity and where it would occur within a watershed. Rather than estimating stream water flow, the model's strength is in identifying the zones having the highest risk of water scarcity within a watershed as well as a river-basin. Hence, SVWBM fills the gap between current need of water resource management in developing countries and the data requirements of existing, complex models designed for application in developed countries.

SVWBM is based on existing knowledge of hydrological processes. It requires relatively less data. This model is a tool for analyzing temporal and spatial variation in the overall water budget and potential risk of water scarcity at a spatial scale ranging from basin to sub-watershed. A watershed model considers that the precipitation accumulated in a watershed has three components i.e. percolation and soil storage, fraction returned to the atmosphere, and water released from the watershed via runoff or subsurface flow. The water balance equation used in the proposed SVWBM model is a modified version of the equation given by Dingman [59], which is as follows:

$$(P+G_{sy}+T_i)-(ET+I+R+W_s+T_o) = \Delta S \quad \text{.................. (1)}$$

*Where,* P = Precipitation, $G_{sy}$ = Potential safe yield of aquifer, ET = Evapotranspiration, I = Infiltration, R= Surface Runoff, $W_s$ = Water use (in agriculture, industry and residence), $T_i$ = Trans-boundary water inflow, $T_o$ = Trans-boundary water outflow, $\Delta S$ = Change in water storage.
The various steps in calculating the components of SVWBM and data required for their estimation are listed in Figure 1.

**Study Area : Watershed Delineation**

Delineated Digital Watershed

or

Watershed delineation through ArcGIS or SWAT

| Component | Preparation of data in required format | | Data_type |
|---|---|---|---|
| | Direct | Indirect | |
| P | Grid data/ Uniform grid data | Interpolation (krigging/isohyetal) | Monthly average/ daily precipitation data of different stations |
| $G_{sy}$ | Grid data | Use of MODFLOW model / Multi-Criteria Evaluation Technique | Depth of water table, Hydraulic conductivity, Specific yield, Recharge rate, etc |
| ET | Grid data | Isopleth map / RS-GIS techniques (e.g. NDVI to ET) | Satellite imageries, monthly average PET/AET |
| R | Grid data | SCS-CN method | Satellite imageries, landuse, monthly average rainfall, soil map, DEM |
| I | Grid data | Isopleth map/ SCS-CN method | Outputs of SCS-CN method estimating runoff |
| $W_s$ | Grid data | Political boundary wise water use map | Block-wise water demand/use data |

***Figure 1:*** *Methodological framework of Spatial Variation in Water Budget Model*

**2.1. Preparation of Input Data to SVWBM:**

The steps involved in data creation are discussed as follows:

First, the study region is selected. If the digital river-basin or watershed boundary is not readily available, the area could be delineated using GIS software (such as, SWAT or ArcGIS) or digitized and extracted from a geo-referenced watershed map.

Second, raster grid data which is compatible to ArcGIS 9.1 or greater version is prepared, for each and every input and output components of water budget.

SVWBM supports a number of methods to prepare the input raster grids. They are discussed below:

a) $P/G_{sy}/ET/I/R$ data available in grid format could directly be used in SVWBM, only the spatial extent and projection system should be same with the delineated watershed polygon data.

b) Isopleths are to be generated and classified zones could be prepared for the watershed and these could be transformed to raster data from the available $P/G_{sy}/ET/I$ data from the respective weather stations using the spatial interpolation techniques such as Kriging. The accuracy of this data set depends on the number of weather stations in the study areas.

c) If the data is available for only one station, a uniform grid, i.e., the same data assigned to every grid cell of the watershed in a similar fashion as the SWBM model [24]. This technique is followed to create raster data for $T_i$ and $T_o$, because it is assumed that the volume of trans-boundary water inflow is available equally for the entire area and outflow takes place through a particular location.

d) Often, data is available on the basis of administrative boundaries such as block, district and state. Depending on the purpose of study, these data can be used to prepare raster data following the above procedures. Here, the polygons are formed following the administrative boundaries. Generally, estimation of the component, Water Use ($W_s$), is computed following this technique.

e) In case of evapotranspiration measurement, the RS-GIS based methods, e.g., NDVI to ET/PET [34], [6], [1], can be used. For surface runoff estimation, SCS-CN method is preferable. The input GIS layers for SVWBM should be in raster format.

**2.2. Model Execution:**

The grid-data must be represented by an integer which must correspond to a particular class. The grid having the lowest integer value would be assigned '1' as its rank, (i.e., very low) and gradually the rank would increase with higher value of integer. The 'Grid Editor' in ArcGIS can be used to manually convert the integer values to its corresponding ranks. For example, in figure 2, the white boxes represent the lowest value and hence, assigned rank '1' whereas the darkest black boxes get the highest rank '5' having the greatest integer value. But, this manual process would be difficult and time consuming, if a large number of classes are present. Therefore, an automatic 'integer to rank' conversion procedure has to be developed. However, grid maps of all the input and output components have to be converted into 'rank-maps'.

The 'rank maps' of the three input components as well as the five output components are summed up, separately. For example, in figure 2, the 'A' and 'B' are the two sets of 'rank -map'. The weight of column1-row1 of A-set, i.e., '5' is summed with the rank of column1-row1 of B-set, i.e., '4' and the result is put to the column1-row1 grid of the resultant map. This summation would generate a total input and a total output map.

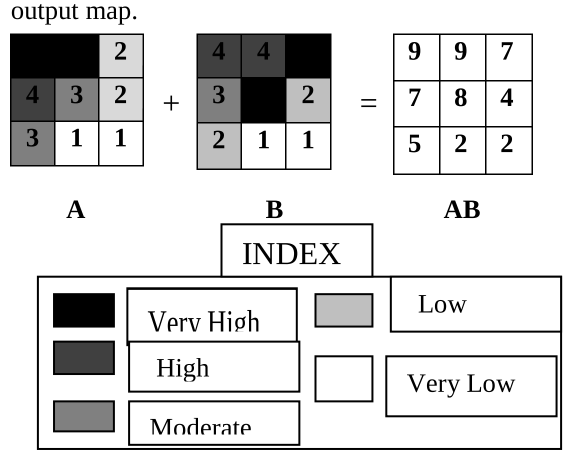


***Figure 2***. *Procedure of integer to rank conversion and summation of rank -maps*

Finally, the spatial variation of change in water storage condition ($\Delta S$) would be obtained by subtracting the rank of individual cell of the total output map from the corresponding cell-ranks of the total input map (refer Figure 3). Thus, SVWBM, is able to identify the zones of positive, negative and neutral water balance within a watershed.

$$\begin{array}{|c|c|c|}\hline \mathbf{8} & \mathbf{8} & \mathbf{7} \\ \hline \mathbf{7} & \mathbf{6} & \mathbf{4} \\ \hline \mathbf{5} & \mathbf{2} & \mathbf{2} \\ \hline \end{array} \; - \; \begin{array}{|c|c|c|}\hline 9 & 6 & 8 \\ \hline 6 & 8 & 5 \\ \hline 2 & 2 & 3 \\ \hline \end{array} \; = \; \begin{array}{|c|c|c|}\hline \mathbf{-1} & \mathbf{2} & \mathbf{-1} \\ \hline \mathbf{1} & \mathbf{-2} & \mathbf{-1} \\ \hline \mathbf{3} & \mathbf{0} & \mathbf{-1} \\ \hline \end{array}$$

**Input (I)** **Output (O)** **Changes in Water Storage (ΔS)**

***Figure 3**. Subtraction of total ouput from total input and final output of SVWBM*

It should mention that accuracy of the final output depends on accuracy in estimation of the components.

### 2.3. Advantages:

The major advantages of SVWBM model are as follows:

a) Applicability on both gauged and ungauged catchments at any desired temporal scale;
b) Capability of dealing with spatial variability associated with any components;
c) Low data requirement and flexibility in methods of estimation of different components;
d) The user-advantage of SVWB model is that one can add or remove any component depending on the purpose of study of water balance without hampering its successful execution; and
**e)** The model can simulate different scenarios which would help the local decision-making process in future development planning.

## 3. Conclusion:

The model, SVWBM, is specifically designed to assess the status of water balance identifying whether the change in water storage is in negative, positive or neutral condition. The model is not suitable for engineering specific hydrologic application or for accounting or simulating peak flow, sediment loading, soil erosion or pollutant loadings.

The techniques to automate functions, like, spatial interpolation to generate isohyets, integer to rank conversion, summation and subtraction of ranks, pixel-wise, can be programmed in a GIS environment to facilitate ease of application of this model.

Hence, SVWBM is suitable for the purpose of assessing the status of water balance of Indian watershed fulfilling all the six criteria discussed above.

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