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Pedotransfer Functions in Hydrologic Modelling for Predicting the Effect of Changes in Soil Types on Watershed Hydrology

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Abstract: Soil water dynamics is becoming a more important component in a watershed model for realistic simulation. But the modellers are handicapped by the non-availability of required soil hydrologic data. The pedotransfer functions (PTF) come in handy to bridge the gap in data availability and pave way for developing more hydrologic models. Few organisations have come forward to collect the global soil data, and the PTFs are devised to serve the global requirement. The 'ensemble' or 'multi-modelling' approach of combining more than one PTFs to get the value of a soil property, is followed in developing Watershed Processes Simulation (WAPROS) model. The model is applied to a natural watershed, calibrated and evaluated with a 'very good' rating. The performance of the model indicates the functional reliability of the PTFs used in the model. As all the required soil properties are fully coupled with PTFs, the model is used to develop scenario for changes in soil types. Five types of soils based on textural classification, sandy loam, sandy clay loam, sandy clay, clay loam and silty clay loam are considered for the scenario study. The soil types are sequenced based on decreasing sand contents and compared with the trends in simulated values of infiltration, evapotranspiration and channel flow. The scenario outputs developed by the model for changes in soil types are logical and interpretable. The simulated outputs for various types of soils, considered to be potential candidates in planning stage, may be simulated and combined using multi-modelling methods to arrive at an acceptable output.

Keywords: *pedotransfer functions, ensemble, hydrologic model, scenario studies, multi-modelling*

1. Introduction

The hydrologic models require more elaborate soil water sub-model than before, for realistic simulation at the watershed scale. But the modellers are handicapped by the paucity of required soil hydrologic data due to lack of measurement instrumentation, spatial variability of data, high cost in collection of data and more time lag in acquiring the data [15]. The pedotransfer functions (PTF) come in handy to bridge the gap in data availability. Now more hydrologic models are developed, utilising the potentials of PTFs.

But the PTFs are developed in various parts of the world, often with the bias towards the characteristics of local soils. Some researchers and organisations have come forward and created large international databases, such as UNSODA, HYPRES, WISE, NRCS, etc. and helped devising the PTFs for general and wider applications [12].

Now 'ensemble' or 'multi-modelling' approach is gaining more acceptances [3] [4]. This procedure is followed in developing a new Watershed Processes Simulation (WAPROS) model. The model is applied to a natural watershed and the evaluation results give a 'very good' rating for the model. This *inter alia* endorses functional reliability of PTFs used in the model [22].

As all the required soil properties are coupled with PTFs, the WAPROS model has acquired the capability of developing scenario for hypothetical changes in soil types. This is similar to the scenario studies often embarked for hypothetical changes in climate and land use, which are considered as having potential practical interpretations. These studies address the question of 'what will happen, if that happens?'

The scenario study for changes in soil types may first look to be of no practical relevance, as soil type is not going to alter, or the change is not going to happen. But this lays good foundation for multi-modelling application in hydrology, in which the model outputs for various combinations of disputed soil types can be combined to produce an acceptable output, when in fact a particular soil type under consideration is questioned. These studies will address the question of 'what will happen, if the soil type chosen is not correct?'

As the spatial variabilities of soil characteristics are unavoidable in a watershed, this kind of scenario study for changes in soil types and multi-modelling will also become unavoidable. The scenario outputs developed for five soil types are reasonable and the projections point to the potential use of this method in future studies.

The applications of PTFs in hydrologic modelling and scenario development are discussed separately in this paper.

2. Pedotransfer Functions

The PTF is a predictive function devised to estimate a soil hydrologic property (few prefer the term soil hydraulic property) from the known values of easily measurable basic soil properties. Normally particle-size fractions, bulk density and organic matter content are regressed against the required soil property and the regression equation, with coefficients as weights, intercepts and error term, becomes the PTF. PTFs help in translating ‘data we have’ into ‘data we need’ [1], or the raw soil data acquire value addition and information with the PTFs.

PTFs help to substitute direct measurements, which are laborious, costly and time consuming [21]. The biggest advantage of using the PTFs is that it addresses the problem of spatial variability, by estimating the soil parameters having high coefficient of variations (> 100%) in the field from the measured inputs having low coefficient of variations (< 30%) [15].

A soil property can be predicted by different PTFs of different complexities. The complexity is determined by the number of input parameters considered; generally more the parameters better the result expected. However a PTF is often selected based on the number of basic data available on hand.

2.1. Applications of PTFs

The development of Geographical Information System (GIS) has spurred wider applications of PTFs [12]. The PTFs are developed for various types of soil properties that find applications in soil science, hydrology, soil erosion, soil contamination, etc. The soil properties estimated by the PTFs for hydrologic applications include: (a) physical properties like bulk density, porosity, mean particle diameter, etc., (b) soil water contents like saturation moisture content, field capacity, wilting point and residual moisture content, (c) infiltration parameters like wetting front suction head, saturated hydraulic conductivity, etc. and (d) soil water characteristic parameters like pore size index, air entry potential, etc. The PTFs, besides generating values of un-measured soil properties, help to minimise the input data requirement for the simulation models.

2.2. Ensemble or multi-modelling of PTFs

Normally a PTF developed from a set of soil data does not perform well in other soils. Some PTFs are evaluated to be more suitable for one type of soil and unsuitable for other types of soils [9] [21]. Few PTFs are evaluated to underestimate some and overestimate other soil properties [20]. It is reported that no single PTF can be described as the most suitable for all soils [4] [8]. These constraints with single PTF necessitates the shift to multi-modelling [12].

The method considers selection of many useful PTFs for a soil property, and estimation of the property value either by averaging or regressing the output values [3]. This approach called as ‘ensemble’ or ‘multi-modelling’ is gaining more acceptance [4] [12] and it is followed in developing a new WAPROS hydrologic model. The ensemble approach decreases the errors in individual PTF [4] and improves its reliability [11]. The ensemble output is also reported to be significantly better than the best single PTF [8]. While estimating the water retention functions, it is reported that PTF ensemble gives two times smaller errors than laboratory data [3].

In WAPROS model, more number of reasonably performing PTFs for every soil hydrologic property are selected, the outputs of individual PTF are obtained and then their average is estimated by ensemble approach [4] [11]. The details of PTFs used for each of the soil property and the methods of ensemble are shown in table: 1.

2.3. Limitations of PTFs

The PTFs have been developed under different geologic and climatic conditions, using different datasets and its universal application are always doubted. The versatility and applicability of PTFs for humid and tropical soils across continental boundaries are proved in few studies [20].

The variations of soil properties along the slope and landscape are said to be ignored by the PTFs, but it is defended as being taken care by the differences in soil particle distribution [12] and appropriate sampling. The presence of soil cover, crust, coarse fragments and rock can affect the soil properties, for which necessary adjustment PTFs have also been devised [13] [14].

The importance of soil structure in soil water interactions and its omission, due to its semi-quantifiable nature, in the formulation of PTFs are also pointed out. The inclusion of organic matter content, bulk density and porosity in the PTFs is reported to offset this deficiency [16].

The applicability of PTFs to soils other than those from which these are derived, causes uncertainty in estimates [5]. Other sources of uncertainties are: error in measuring basic soil data (inputs), error in accounting for spatial variability of input data, error in PTF equations and error in models [12]. Apart from these, the propagation of error in the model also causes uncertainty in simulations of the model [7]. The estimation of these uncertainties and its elimination in the model are difficult [22], but a good evaluation rating for the model can be an evidence of low uncertainty.

The top soil disturbances by manure application, cultivation, ploughing and erosion cause changes in soil properties temporarily and temporally, and are not fully represented by PTFs [12], which need to be addressed.

3. Multi-modelling of model outputs

Hydrologic simulation models find more applications during the planning or pre-project stage. When a reservoir project is planned, the peak and the annual simulated channel flow from the model form the basis to decide the volume of impoundment and the length of surplus. The whole exercise is done on the presumption that the soil properties of the catchment are correctly identified and given as inputs to the model. When the soil type considered for the catchment is questioned, in favour of one or more other types, simulated flows for each such contesting soil types can be simulated, and an acceptable flow data can be obtained using multi-modelling methods. Scenario study of this kind will be of much use under the stated circumstances. This method can be extended to soil erosion, soil pollution and groundwater studies as well. This multi-modelling approach was used for streamflow forecasts at multiple locations in Colorado [17].

4. PTFs in hydrologic modelling

The PTFs meant for study of soil water characteristics is later applied to hydrologic models [7] [19]. The intended uses or objectives of the hydrologic model decides the details of various components. As WAPROS model is objectivised for simulating watershed hydrology and water balance module, detailed accounting of soil water flow is inevitable. The use of algorithms like Green Ampt infiltration model, and consideration of saturated and unsaturated hydraulic conductivities in soil water flow, mandate use of PTFs in the model, due to impracticality in measuring some inputs.

4.1. WAPROS model

WAPROS is a new lumped, continuous and deterministic hourly model exclusively developed for simulating hydrologic processes and water balance in small and medium sized watersheds of size from 100 to 10000 ha to suit availability of inputs in Indian conditions.

The model simulates 15 hydrologic processes, with 10 hydrologic storages. The hydrologic processes are differentiated into additive and depletive processes and distinctions are made between lumped and elemental processes. The model simulates hydrologic storage positions and process values on hourly basis and integrates hourly data into daily data for use in watersheds where only hourly rainfall and daily channel flow data are available. The model also synthesises elemental processes into lumped processes usable for water balance. The model generates two water balance equations, closure errors for all 10 storages and water balance ratios.

4.2. Application of WAPROS model

The model is applied to a real watershed, called ‘Ebbanad’, which is located in the Nilgiris district of Tamil Nadu State, India. The centroid of the watershed is at 11^0 $26^{'}$ 15”N. Ebbanad is a mountainous watershed in humid agro-climatic region, with a mean elevation of 2084.0 m above MSL. The stream originates from the Doddabetta peak and joins the Moyar River. The total area of the watershed is 3582.0 hectares, with a drainage density of 2.904 km per sq. km. The land use pattern in the watershed is: 1722 ha under forest; 1797 ha under agricultural crops including tea plantations; and 63 ha under impervious area like rocks, habitations and roads. The watershed is treated with soil and water conservation measures like bench terraces, contour stone walls, contour trenches in the hill side and contour bunds and check dams in the plains, covering an area of 1218.0 ha.

The average longitudinal slope of the watershed is 7.01 % and the average cross sectional slope is 32.52 %. Five different types of soils are spread across the watershed and the averages of the sampled soil constituents are estimated as: sand: 55.01 %; silt: 17.40 %; clay: 27.59 %; organic matter: 1.45 %; and coarse fragments: 1.23 %. These values are used as inputs to the PTFs and the model [19].

The model has six parameters, which are estimated by inversion manually. The calibration criteria include: maximization of Nash Sutcliffe’s efficiency and Coefficient of determination and minimization of volume deviation error and Root mean square error. Calibration is done with observed data from Ebbanad watershed on split sample procedure and the parameter values are finalized.

4.3. PTFs used in WAPROS model

The details of PTFs employed for estimating different properties of the soils in the WAPROS model are given in table: 1. As shown in the table, the model requires only the following soil constituents, in % by weight basis: sand, silt, clay, coarse fragments and organic matter. The USDA textural classification is adopted for separates sizes and soil classes. The SOILPTF subroutine generates many outputs, of which values of 14 properties, as indicated in the table, are transferred to the model for hydrologic simulation. The bulk density, porosity, CEC, etc. can be estimated easily in the field or laboratory [2], but these are estimated by PTFs to reduce the errors due to spatial variability and to provide complete linkage to all soil properties to facilitate scenario development. The different PTFs used for each of the soil property are also indicated in the table. These PTFs are sourced from various published literature [5] [10] [18].

While selecting the PTFs, the outputs of various PTFs are individually evaluated for Ebbanad soil types, and then compared to the standardised values for different soil textures of USDA classes [15]. For the soil textures that could not be sampled locally, such as for sand, silt, clay, and silty clay, the USDA standard values are taken as the base values. The soil properties such as geometric mean diameter, fractal dimension, wetting front suction head and pore size index could not be measured in the field or laboratory, for lack of instrumental facilities, and the published values are taken as reference values [10]. Few PTFs that deviate more beyond the normal values have been dropped.

The ensemble procedures of estimating different soil properties are explained below. The swelling pore volume, residual moisture content and wetting front suction head are estimated with only one PTF and its estimates are retained as such. The fractal dimension of soil particles, cation exchange capacity(CEC), saturated moisture content and pore size index are estimated as arithmetic averages. The geometric mean diameter of soil particles is estimated as geometric mean. The bulk density, field capacity and wilting point are estimated as weighted averages. The saturated hydraulic conductivity is estimated as weighted geometric mean. The soil porosity and CEC per kg of clay are estimated from bulk density and CEC respectively.

Table 1 *Pedo Transfer Functions (PTF) used for estimating soil hydrologic properties in WAPROS model*

S.No	Details of Inputs and Outputs	Values
A	Inputs to the model	
	Sand content of soil [% kg/kg]	55.01
	Silt content of soil [% kg/kg]	17.40
	Clay content of soil [% kg/kg]	27.59
	Coarse fragments content [% kg/kg]	1.23
	Organic matter content [% kg/kg]	1.45
B	Outputs of the model	
I	General Basic Soil Properties	
1	Bulk Density [gm/cc] [Mgm/m3]	
	BD R1 Rawls I Bulk Density	1.4631
	BD R2 Rawls II Bulk Density	1.5198
	BD Ws Wosten Bulk Density	1.3819
	BD Arith Averaged Bulk Density	1.4550
	BD Weighted Average BD	1.3976
	BD Om Gravel Adj. Bulk Density	1.2989
2	Soil Porosity [m3/m3]	
	Porosity Estimated From BD	0.5099
3	Swelling Pore Volume [m3/m3]	
	BZ Bruand Zimmer Pore Volume	0.3154
4	Geometric MD of soil particles	
	GMD Cbr Campbell Revised GMD	0.0206
	GMD Cbs Campbell Shiozava GMD	0.0799
	GMD Cl Calcptf GMD	0.0317
	GMD Estimated from Part.Size	0.0799
	GGMD Geometric Mean of GMD	0.0587
5	Fractal Dimension of soil particles [-	
	FDim Fractal Dimension Ogawa I	1.3969
	FDim Fractal Dimension Ogawa II	1.4044
	FDim Fractal Dimension Ogawa III	1.6730
	FDim Arith Averaged Fractal	1.4914
6	Cation Exch Capacity [c.moles/Kg]	
	CEC Mb McBratney CEC	18.105
	CEC Mj Majid Rashidi CEC	15.263
	CEC Br Breeuwsma CEC	15.970
	CEC Kv Keshavarzi CEC	17.260
	CEC Am Arithmetic Averaged CEC	16.650
7	CEC per kg of Clay [c.moles]	
	CECC CEC per kg of Clay	0.6035
II	Soil Water Hydraulic Properties	
1	Saturation Moisture content [m3/m3]	
	SMC Rawls I Sat.Moisture content	0.3369
	SMC Rawls II Sat.Moisture content	0.3453
	SMC Minasny Sat.Moisture content	0.4515
	SMC Minasny II Sat.Moisture	0.3516
	SMC Wosten I Sat.Moisture content	0.4669
	SMC Scheinost II Sat.Moisture Cont.	0.4701
	SMC Cosby I Sat.Moisture content	0.4197
	SMC Cosby II Sat.Moisture content	0.4167
	SMC Zacharias Sat.Moisture content	0.4442
	SMC Arithmetic Averaged SMC	0.4114
2	Field Capacity [m3/m3]	
	FC Bkh Burrows Kirkham Field	0.2643
	FC Br Brakensiek Field Capacity	0.2805
	FC Rw Rawls I Field Capacity	0.1906
	FC Rl Rawls II Field Capacity	0.2721
	FC Ht Hutson Field Capacity	0.3098
	FC Gm Rawls GMDH Field	0.2771
	FC Rmn Minasny Field Capacity	0.3148
	FC Mr Merdun Field Capacity	0.2522
	FC Adh Adhikary Field Capacity	0.2362
	FC Amj Al Majao Field Capacity	0.2449
	FC Arithm Averaged Field Capacity	0.2643
	FC Weighted Avg Field Capacity	0.2768

3	Wilting Point [m3/m3]	
	WP Bk Brakensiek Wilting Point	0.1714
	WP Rw Rawls Wilting Point	0.1772
	WP RL Rawls Leachm Wilting Point	0.1723
	WP Gm Rawls GMDH Wilting Point	0.1639
	WP Bs British Soil Wilting Point	0.1844
	WP GL Gupta Larson I Wilting	0.1779
	WP Rmn1 Minasny I Wilting Point	0.1914
	WP Adh Adhikary Wilting Point	0.1285
	WP Amj Al Majao Wilting Point	0.1430
	WP Can Canarache Wilting Point	0.1100
	WP Arithm Averaged Wilting Point	0.1620
	WP Weighted Avg Wilting Point	0.1336
4	Residual Moisture content [m3/m3]	
	RMC Rawls Res.Moisture content	0.1050
5	Saturated Hydraulic Cond	
	SKS Minasny I	47.174
	SKS Minasny II	22.759
	SKS Julia II Sat.Hyd.Conductivity	13.778
	SKS Wosten II	25.862
	SKS Veerecken	16.352
	SKS Li Saturated Hyd.Conductivity	5.9489
	SKS Jabro Saturated Hyd.Conductiv.	0.9103
	SKS Spychalski I	33.195
	SKS Saxton Sat.Hyd.Conductivity	8.1795
	SKS Jarvis I Sat.Hyd.Conductivity	12.214
	SKS Weynants	15.226
	SKS Wt Geom Mean Sat.Hyd.Cond	21.832
III	Green-Ampt Infiltration Model	
1	GA Rawls WettingFront	841.33
2	BC Lambda Pore Size Index [-]	
	BC Rawls Lambda	0.2700
	BC Cosby I Lambda	0.1371
	BC Cosby II Lambda	0.1376
	BC Cosby III Lambda	0.1346
	BC Saxton Lambda	0.1292
	BC Smettem Lambda	0.1394
	BC Grewal Lambda	0.0731
	BC Arithmetic Averaged Lambda	0.1458

Thereafter the PTF submodel is tested at different stations, the weightages are suitably revised and the reliabilities of the ensemble PTFs are ensured for different soil types. In respect of saturated hydraulic conductivity, no method gives consistent estimates for the soils, owing to high spatial variability. Hence the USDA standard values [10] are taken as the base values for different classes of soils and the weighted geometric mean of the values of selected PTFs are estimated to match the class values. For application at a watershed scale, the spatial variability of hydraulic conductivity is assumed to follow lognormal distribution and the areal average value of saturated hydraulic conductivity is estimated, using the author derived equation, having sample shifting factor and coefficient of variation. The analytical and testing part of the methodology is not presented here.

4.4. Functional application of soil properties

The values of soil properties generated by the model, using PTFs, are either applied directly in the model or are used for estimating other soil properties for being used in the model. The itemised functions of different soil properties in the model are given below:

a. Bulk density: porosity, field capacity, wilting point, saturated moisture content, residual moisture content;
b. Porosity: field capacity, wilting point, saturated moisture content, residual moisture content, wetting front suction head, pore size index (lambda);
c. Swelling pore volume: macro pore flow;
d. Geometric mean diameter of soil particles: soil detention, fractal dimension of soil particles;
e. Fractal dimension of soil particles: macropore flow;
f. CEC: wilting point, pore volume, CEC per kg of clay;
g. CEC per kg of clay: bulk density;
h. Field capacity, wilting point, saturated moisture content, residual moisture content: all storages;
i. Saturated hydraulic conductivity: Green Ampt infiltration equation, permeability:
j. Wetting front suction head: Green Ampt infiltration equation;
k. Pore size index (lambda): fractal dimension of soil particles;

From the above, it could be seen that all the soil hydrologic properties are fully coupled with PTFs in WAPROS model. This arrangement facilitates estimation of all the required soil hydrologic properties using only the five soil inputs, which helps in hydrologic scenario development for changes in soil types, with just changes in these inputs.

4.5. Performance of WAPROS model

The simulated channel flows from WAPROS are compared to the observed flows from Ebbanad watershed with nine evaluation criteria, the formulations of which are given below (Simulated flow = X and Observed flow = Y):

$$1:\ R^2 = \text{Coefficient of Determination} = (r)^2$$

$$= \left[\frac{\left(N\sum X_i.Y_i - \sum X_i.\sum Y_i\right)^2}{\left[N\sum X_i^{\,2} - \left(\sum X_i\right)^2\right]\left[N\sum Y_i^{\,2} - \left(\sum Y_i\right)^2\right]} \right]$$

$$2:\ \text{Mean Error} = ME = \frac{1}{N}\left[\sum (X_i - Y_i)\right]$$

3: Volume Deviation Error

$$= VDE = \left[\frac{\sum(X_i - Y_i)}{\sum Y_i} \right]$$

4: Root Mean Square Error = *RMSE*

$$= \sqrt{MSE} = \sqrt{\frac{1}{N}\left[\sum(X_i - Y_i)^2\right]}$$

5: *RSR* = (RMSE ÷ SD of Observed Flow)

$$= \text{Relative RMSE} = R.RMSE = \left[\frac{RMSE}{\sigma y} \right]$$

6: Nash Sutcliffe's Efficiency = NSE

$$= CE = \left[1.0 - \frac{\sum(X_i - Y_i)^2}{\sum(Y_i - \bar{Y})^2} \right]$$

7: Chiew McMahon's Efficiency = *CME*

$$= NSE(\sqrt{\ }) = \left[1.0 - \frac{\sum\left(\sqrt{X_i} - \sqrt{Y_i}\right)^2}{\sum\left(\sqrt{Y_i} - \sqrt{\bar{Y}}\right)^2} \right]$$

8: Kling – Gupta Efficiency Index = KGE_{α};

$$ED_1 = \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2}$$

r = Correlation Coefficient;

$$\alpha = \left(\frac{\sigma x}{\sigma y} \right); \quad \beta = \left(\frac{\bar{X}}{\bar{Y}} \right);$$

$$KGE_1 = KGE_{\alpha} = (1.0 - ED_1)$$

9: Willmott's Refined Index = d_r

$$= \left[1.0 - \frac{\sum|X_i - Y_i|}{2\sum|Y_i - \bar{Y}|} \right].$$

In model evaluation, the best values for Coefficient of determination, Nash-Sutcliffe's efficiency, Chiew-McMahon's efficiency, Kling-Gupta efficiency (α) and Willmott's refined index (dr) are 1.0 and the best values for Mean error, Volume deviation error, Root mean squared error (RMSE) and Ratio of RMSE to Standard deviation of observed flows (RSR) are 0. The results of model evaluation with respect to the hourly and the daily data are:

Evaluation criteria	Hourly	Daily
R2 Coeff of determination	0.8622	0.9072
ME Mean error	–0.0714	–0.0714
VDE Volume deviation error	–0.0583	–0.0583
RMSE Root mean squared error	0.6349	0.4913
RSR Ratio of RMSE to SD obs	0.3758	0.3117
NSE Nash-Sutcliffe's efficiency	0.8588	0.9028
Chiew-McMahon's efficiency	0.7548	0.8028
KGE Kling-Gupta efficiency (α)	0.9027	0.9248
Willmott's refined index (dr)	0.7911	0.8122

It could be seen that the performance of the model for hourly and daily data imply a 'very good' rating for WAPROS model. The very good performance of the WAPROS model and water balance lend more support to develop hydrologic scenario. As the soil properties are fully coupled by the PTFs, the model is capable of simulating hydrologic changes not only for changes in climate and land use but also for changes in soil type. The results of model evaluation can also be considered as results of functional evaluation of PTFs [22].

5. PTFs in scenario modelling

While developing hydrologic scenarios for climate changes and land use changes, all the inputs and the values of calibrated parameters of Ebbanad watershed are kept unchanged, and only the concerned values of climate or land use parameters are changed respectively. This is similar to the celebrated principle of *ceteris paribus*, from economics. Here the climate and the land use are the imposed variables on the calibrated hydrologic model and its manipulation is less cumbersome.

When it is objectivised to develop a model to simulate scenario for different types of soils, all the soil hydrologic processes in the model are required to respond to the changes. The soil and water interactions are pervasive all through the model and gets multiplied by the changes in soil types. Hence the scenario study for changes in soil types requires lot of changes in soil inputs, which could not often be measured for the hypothetical soil types. These difficulties dampen the spirit of venturing into this kind of scenario modelling for changes in soil types. The availability of numerous PTFs offer scope for producing multiple outputs. Hence PTFs are desperately required to link all the soil hydrologic parameters, to facilitate smaller number of changes in soil inputs to trigger the whole soil water processes in the model. The precedence of similar studies could not be traced.

As WAPROS model is developed with fully coupled soil PTFs, the changes in watershed hydrology could be simulated for changes in soil types, with smaller changes in soil inputs. Thus fully coupled PTFs provide avenue for developing hydrologic scenario for changes in soils in a watershed.

But as with every scenario study, the evolutionary and associated changes, like vegetation-environment compatibility, are not considered. That is changes in climate or soil will be also accompanied by changes in vegetation as well, but such possible effects are to be disregarded, for the benefit of screening and studying the effects of required changes alone. As the scenario studies deal with hypothetical or futuristic changes for which no observed data are available, calibration is not feasible and hence results of such scenario studies are often considered as projections.

5.1. Soil Textural Classes for Scenario Development

The combination of three soil constituent fractions make up 12 soil classes (few advocate 11 classes). But the soil classes often encountered in the watersheds are: sandy loam, sandy clay loam, sandy clay, clay loam and silty clay loam. Hence it has been proposed to carry out scenario studies for these five types of soils. Based on decreasing sand content and increasing clay content, the soil types are arranged in an order and coded as A, B, C, D and E, for clarity in discussion. The contents of soil constituents (% by weight) for each soil class [6] and the specific values of constituents (% by weight) considered for the soil type under scenario study are given in parenthesis, as below:

No.	Soil classes	Sand%	Silt %	Clay%
A	Sandy loam	40-80 (60)	0-50 (30)	0-20 (10)
B	Sandy clay loam	45-80 (60)	0-28 (15)	20-35 (25)
C	Sandy clay	45-65 (55)	0-20 (10)	35-45 (35)
D	Clay loam	20-45 (30)	15-53 (35)	27-40 (35)
E	Silty clay loam	0-20 (10)	40-73 (55)	27-40 (35)

The constituent %age values in parenthesis are adopted for characterising the specific class of soil in WAPROS model. For scenario studies, it is presumed that five types of changes in soil classes create five types of artificial or ersatz Ebbanad watersheds, differentiated only by the soil types and their hydrologic behaviours are simulated.

5.2. Hydrologic Scenario for Different Soil Classes

The Ebbanad watershed soils have average coarse fragments content of 1.23% (by weight) and organic matter content of 1.45% (by weight), which are not included in the % age make-up of the above soil classes. For maintaining uniformity and to avoid distraction in inference of output data, the contents of coarse fragments and the organic matter are also kept unchanged. To meet the condition of *ceteris paribus*, the rainfall, the contour ploughing practised for agricultural cropping, the soil and water conservation measures coverage and the two factors for obtaining areally averaged saturated hydraulic conductivity are also kept unchanged.

For each soil class selected and for the specified soil constituents, the values generated for different soil properties by the model PTFs are given in table: 2. For comparison the respective values for Ebbanad soils are also given. These values of soil properties are used as inputs by WAPROS model, for generating simulated hydrologic outputs.

Table 2 *Values of soil hydrologic properties generated by PTFs for selected soil textural classes*

No	Inputs and outputs	Ebbanad soil	Sandy loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam
I	INPUTS TO THE MODEL						
1	Sand content of soil [% kg/kg]	55.01	60.00	60.00	55.00	30.00	10.00
2	Silt content of soil [% kg/kg]	17.40	30.00	15.00	10.00	35.00	55.00
3	Clay content of soil [% kg/kg]	27.59	10.00	25.00	35.00	35.00	35.00
4	Coarse fragments content [% kg/kg]	1.23	1.23	1.23	1.23	1.23	1.23
5	Organic matter content [% kg/kg]	1.45	1.45	1.45	1.45	1.45	1.45
II	OUTPUTS OF THE MODEL						
1	Bulk density[gm/cc] [Mgm/m3]	1.2989	1.4150	1.3149	1.2553	1.2561	1.2577
2	Soil porosity [m3/m3]	0.5099	0.4660	0.5038	0.5263	0.5260	0.5254
3	Swelling pore volume [m3/m3]	0.3154	0.3438	0.3171	0.3120	0.3120	0.3120
4	Geometric MD of soil particles [mm]	0.0587	0.1330	0.0769	0.0448	0.0186	0.0093
5	Fractal dimension of soil particles [-]	1.4914	1.4344	1.4854	1.5070	1.5050	1.5037
6	Cation exchange capacity CEC [c.moles/kg]	16.6134	9.2653	15.6910	19.1025	19.1025	19.1025
7	CEC per kg of clay [c.moles]	0.6035	1.0275	0.6285	0.5524	0.5524	0.5524
8	Saturation moisture content [m3/m3]	0.4114	0.3677	0.4009	0.4245	0.4501	0.4673
9	Field capacity [m3/m3]	0.2768	0.2096	0.2586	0.3000	0.3377	0.3530
10	Wilting point [m3/m3]	0.1336	0.0589	0.1222	0.1643	0.1669	0.1682
11	Residual moisture content [m3/m3]	0.1050	0.0588	0.1012	0.1182	0.1106	0.1045
12	Saturated hydraulic conductivity [mm/hour]	21.8321	35.5433	25.1681	18.8577	12.7829	10.3340
13	GA Wetting front suction head [mm]	841.33	1325.49	1042.20	778.69	488.17	477.46
14	BC Lambda Pore size index [-]	0.1458	0.2527	0.1539	0.1225	0.1311	0.1351

The WAPROS model is run for each soil class to generate simulated data for the modified watershed. The hydrologic data simulated by the model for five types of soils form the basis for the scenario study. The abstract details of simulated hydrologic data for selected textural classes of soils are given in table: 3. The important water balance parameters characterizing the hydrologic changes are given in table: 4. The changes in lumped and elemental processes of channel flow caused by changes in textural classes of soils are given in table: 5. The simulated channel flows for different soil types are evaluated with respect to the channel flow simulated for Ebbanad soils as the basis and the resulting changes in performance of the model are given in table: 6.

6. Results and Discussion

For clarity in discussion, the soil types are arranged in the order of decreasing sand content, as A, B, C, D and E. The values of hydrologic processes across soil types differ distinctly, but also fit in distinct patterns. To capture the pattern of variation along A, B, C, D and E, the highest values are indicated as 'H' and the lowest values are indicated as 'L'. The patterns of variation are identified as: LH - vary from low to high; HL - vary from high to low; LHL - vary initially from low, rise to high and fall to low; and HLH - vary initially from high, fall to low and rise to high.

6.1. Soil Properties Generated by PTFs

The values of soil properties estimated by the PTFs of the model are given in table: 2 against A, B, C, D and E soil types. The soil properties of Ebbanad watershed consistently fall between the values of sandy clay loam and sandy clay. The actual soil constituents of the watershed indicate the texture as sandy clay loam and hence the PTF generated values for Ebbanad are considered acceptable.

Across the A, B, C, D and E soil types, the constituent inputs vary as: sand contents follow HL; clay contents follow LH and the silt contents follow HLH patterns; and the outputs vary as: (a) the bulk density and the pore size index (lambda) follow HLH; (b) the soil porosity, the fractal dimension of soil particles and the residual moisture content follow LHL; (c) the swelling pore volume, the geometric mean diameter of soil particles, the CEC per kg of clay, the saturated hydraulic conductivity and the wetting front suction head follow HL; (d) the CEC, the saturation moisture content, the field capacity and the wilting point follow LH pattern.

From the variability patterns, it can be inferred that the 'c' group properties, the swelling pore volume, the geometric mean diameter of soil particles, the CEC per kg of clay, the saturated hydraulic conductivity and the wetting front suction head are more influenced by sand content, as these match the sand content pattern of HL; the 'd' group properties, the CEC, the saturation moisture content, the field capacity and the wilting point are more influenced by the clay content, as these match the clay content pattern of LH. The 'c' and 'd' groups of properties show opposing trends.

Table 3 *The abstract details of simulated hydrologic data for various textural classes of soils*

No	Simulated hydrologic data	Sandy loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam
1	Sum of rainfall (mm)	543.84	543.84	543.84	543.84	543.84
2	Total infiltration (mm)	403.91	398.94	395.05	391.89	391.08
3	Total evapotranspiration (mm)	202.70	214.97	224.06	224.29	216.48
4	Total channel flow (mm)	408.89	321.43	186.30	128.84	129.29
5	Maximum simulated flow (m^3/s)	10.7045	10.7044	8.9010	8.8695	8.8614
6	Minimum simulated flow (m^3/s)	0.0446	0.0422	0.0051	0.0001	0.0001
7	Mean of simulated flow (m^3/s)	1.8034	1.4176	0.8217	0.5682	0.5702
8	Median of simulated flow (m^3/s)	0.9594	0.7559	0.2797	0.0625	0.0643
9	Coeff of variation of simulated flow (cv)	1.0826	1.1785	1.5764	2.1435	2.1336

Table 4 *Water balance parameters characterizing the hydrologic changes*

No	Water balance parameters (mm)	Sandy loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam
1	Sum of all storages at start	685.94	760.33	760.33	760.33	760.33
2	Sum of all storages at end	618.19	767.78	893.82	951.05	958.40
3	Sum of all addition processes	2146.84	1928.78	1608.04	1441.06	1420.39
4	Sum of all depletion processes	2214.59	1921.34	1474.56	1250.34	1222.31
5	Water storage at the end in upper layer	260.30	320.73	371.36	418.45	438.88
6	Water storage at the end in lower layer	356.99	446.19	521.87	532.42	519.32

7	Sum of addition processes in upper layer	419.14	413.82	409.82	406.67	405.91
8	Sum of addition processes in lower layer	340.18	299.98	241.44	189.14	168.05
9	Sum of depletion processes in upper layer	439.73	405.04	350.41	300.17	278.98
10	Sum of depletion processes in lower layer	375.19	289.12	154.90	92.05	84.07

Table 5 *Changes in sources of channel flow caused by changes in textural classes of soils*

No	Sources of channel flow (mm)	Sandy loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam
1	From overland flow	83.4504	87.6489	90.8901	93.9062	94.9124
2	From base flow	277.6073	191.1294	67.3462	12.3770	12.3758
3	From impervious area	9.0271	9.0271	9.0271	9.0271	9.0271
4	From variable source area	12.5704	12.5473	12.6072	12.4138	12.0290
5	From interflow (upper layer)	2.3305	1.9906	1.5679	1.1122	0.9498
6	From interflow (lower layer)	23.9058	19.0827	4.8599	0.0000	0.0000
7	Total channel flow	408.8915	321.4260	186.2984	128.8363	129.2941

Table 6 *Changes in performance of the model caused by changes in textural classes of soils*

No	Comparative performance	Sandy loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam
1	r2: Coefficient of determination	0.7500	0.9295	0.9257	0.6778	0.6780
2	ME: Mean error	0.6500	0.2642	–0.3318	–0.5852	–0.5832
3	VDE: Volume deviation error	0.5635	0.2291	–0.2876	–0.5074	–0.5056
4	RMSE: Root mean squared error	1.1740	0.5170	0.6226	1.1059	1.1048
5	RSR: RMSE/(SD of observed flow)	0.7171	0.3158	0.3802	0.6755	0.6748
6	NSE: Nash-Sutcliffe’s efficiency	0.4858	0.9003	0.8554	0.5437	0.5447
7	Chiew-McMahon’s efficiency	0.5573	0.8667	0.8704	0.2034	0.2062
8	Kling-Gupta efficiency index (α)	0.3896	0.7672	0.6425	0.4048	0.4060
9	Willmott’s refined index (dr)	0.7075	0.8811	0.8494	0.7337	0.7341

The swelling pore volume is directly related to the geometric mean diameter of soil particles and inversely related to the soil porosity. The pore size index is directly related to the bulk density and inversely related to the soil porosity and the fractal dimension of soil particles. The residual moisture content is directly related to the soil porosity and inversely related to the bulk density.

The values of soil properties across different soil types follow logical interpretations and acceptable physical relationships.

6.2. Hydrologic Scenario for Changes in Soil Types

The abstract details of simulated hydrologic data for various textural classes of soils are presented in table: 3. From the table it can be seen that the total infiltration, the maximum simulated flow (peak flow) and the minimum simulated flow follow HL pattern along ABCDE; the total evapotranspiration follows LHL pattern; the total channel flow, the mean of simulated flow and the median of simulated flow follow HL pattern along ABCED.

It would be intriguing to notice that as clay contents increase along ABCDE soil types, the infiltration, the evapotranspiration and the channel flow decrease for the same rainfall. Normally decrease in one of these components will be accompanied by increase in others, under water balance. The reasons for this anomaly can be seen in table: 4, in which important water balance parameters responsible for these anomalies in hydrologic changes are presented. It can be seen from the table, that much of water is stored in the watershed storages, leaving less to be moved as channel flows. The water storages in the soil upper and lower layers at the end of simulations follow LH pattern along ABCDE and ABECD respectively. It can also be seen that the sum of all addition and depletion processes follow HL pattern along ABCDE, indicating that the hydrologic intensification depends on the sand content of the soils in the watershed.

WAPROS model simulates elemental hydrologic processes, which on summation gives the values of respective lumped processes. The lumped channel flow is further analyzed for source wise contribution as shown in table: 5. From this table, it can be seen that the overland flows follow LH trend; the base flow and interflows follow HL trend. The decrease in sand content and increase in clay content cause substantial decreases in base flow and interflows. The interflow from lower layer ceases in DE soil types. The simulated elemental flows indicate that as sand content increases, the infiltration increases; soil storage decreases; interflows increase; permeability increases; groundwater contribution increases; the base flow increases; and the channel flow increases. The above interpretation equally applies to decreases in clay content also. However from vegetation point of view, more water is stored in the sub-soils of DE soil types that can sustain better crop growth.

The simulated channel flow for Ebbanad soils are evaluated against the observed flow from Ebbanad watershed and reported earlier. As the objective is to evaluate how far the simulations are affected by the changes in soil types, these flows are compared against the simulated flow for Ebbanad soils. The evaluation results are shown in table: 6. It can be seen from the table that the best estimates of evaluation are in the sandy clay loam type of soils, supporting the soil texture of Ebbanad. While reduction in clay content (A) adversely affects the simulation, increase in clay content (C) marginally affects the model efficiency.

In this study, the effects of crop cultivation practices like contour ploughing and soil and water conservation measures also contribute to more infiltration. These conservation conditions are equally applied to all soil types, but the impacts may not be equal for all the soil types, which could not be segregated.

7. Conclusion

The PTFs are devised based on soil textural and other properties to estimate the values of soil properties, which would be otherwise difficult to measure and costly to acquire. The high level of adoption and adaption of PTFs lend credence to the utility of PTFs in all spheres. The PTFs are used in hydrologic models either for a small part or for a complete description of soil water interactions. The 'ensemble' or 'multi-modelling' approach of combining the outputs of more than one PTFs to get the value of a soil property is gaining more acceptance. This procedure is followed to fully couple all the soil properties with PTFs in developing the WAPROS model.

The advantage of using PTFs in WAPROS model is reflected in the evaluation results of the model. The details of PTFs used and the values generated for various soil properties are also presented. The direct and indirect uses of these soil properties in the model are explained.

Then simulation is carried out for different soil types, as a scenario study. The changes in soil properties for changes in soil types are presented. The increasing and decreasing trends in values of soil properties, as sand and clay content increases or decreases, are also discussed.

The changes in hydrologic processes caused by changes in soil types are presented. The water balance components are reported to explain the causes of changes. As the clay content increases, the water holding capacity of soil storages increase and this retention of soil water causes reduction in inter flows, base flow and channel flow. As the sand content increases, infiltration increases, soil water storage decreases and subterranean flow increases. More inter flows and base flows cause the channel flow to increase. Then the simulated channel flows for different soil types are compared against the simulated flow for the Ebbanad watershed soil and the evaluation results are presented. It is very much evident that changes in composition of soil constituents have significant effects on the hydrologic processes and the performance of the model.

When the soil type considered for hydrologic simulation is doubted or proposed with new sets of soil data, this kind of scenario study helps to generate as many sets of outputs as there are contending soil types. These outputs can be combined using multi-modelling methods to arrive at the acceptable output. This approach has more potential in watershed hydrology, soil erosion, non-point pollution and groundwater studies.

References

[1] Bouma, J. Using soil survey data for quantitative land evaluation. *Advances in Soil Science* 9, 177-213. 1989.

[2] Donatelli, M., H. Wosten and G. Belocchi. Evaluation of pedotransfer functions. Pachepsky, Y. A., and W. J. Rawls (Eds). *Development of Pedotransfer Functions in Soil Hydrology*. Developments in Soil Science 30. Elsevier, Amsterdam. 357-363. 2004.

[3] Guber, A.K., Ya.A. Pachepsky, M.Th. van Genuchten, W.J. Rawls, J. Simunek, D. Jacques, T.J. Nicholson, and R.E. Cady. Field-scale water flow simulations using ensembles of pedotransfer functions for soil water retention. *Vadose Zone J.* 5:234–247. 2006

[4] Guber, A.K., Ya.A. Pachepsky, M. Th. van Genuchten, J. Simunek, D. Jacques, A. Nemes, T.J. Nicholson, and R.E. Cady Multimodel simulation of water flow in a field soil using pedotransfer functions. *Vadose Zone J*. 8:1–10. 2009.

[5] Guber, Andrey K. and Yakov A. Pachepsky. *Multimodeling with Pedotransfer Functions*. Documentation and User Manual for PTF Calculator (CalcPTF) Version 2.0. Beltsville

Agricultural Research Center, USDA-ARS. p 23. 2010.

[6] Lal, Rattan and Manoj K.Shukla. *Principles of Soil Physics*. Marcel Dekker, Inc. New York. p 682. 2004.

[7] Leenhardt, D. Errors in the estimation of soil water properties and their propagation through a hydrological model. *Soil Use and Management*. 11, 15-21. 1995.

[8] Liao, Kaihua, Fei Xua, Jinsen Zheng, Qing Zhu and Guishan Yang. Using different multimodel ensemble approaches to simulate soil moisture in a forest site with six traditional pedotransfer functions. *Environmental Modelling & Software*. 57. 27-32. 2014.

[9] Minasny, B and A.B. McBratney. Uncertainty analysis for pedotransfer functions. *European Journal of Soil Science*. 53: 417-429. 2000.

[10] Pachepsky, Y. A., and W. J. Rawls (Eds). *Development of Pedotransfer Functions in Soil Hydrology*. Developments in Soil Science 30. Elsevier, Amsterdam. p 512. 2004.

[11] Pachepsky, Yakov, Andrey Guber, Martinus and Th. van Genuchten. Multi-modeling – an emerging approach to improving process-based modeling of soil systems. *19th World Congress of Soil Science, Soil Solutions for a Changing World*. August 2010, Brisbane, Australia. 32-35. 2010.

[12] Pachepsky, Y. A. and M. Th. van Genuchten. Pedotransfer functions. Jan Glinski, Jozef Horabik and Jerzy Lipiec. *Encyclopedia of Agrophysics*. Springer Science+Business Media B.V. pp 556-560. 2011.

[13] Rawls, Walter J., Donald L. Brakensiek, J. Roger Simanton, and Clayton L. Hanson. Prediction of soil cover and soil rock for rangeland Infiltration. *J of Range Management*. Vol. 41, No. 4. 307-308. 1988.

[14] Rawls, W.J., D.L. Brakensiek and M.R. Savabi. Infiltration parameters for rangeland soils. *J of Range Management* 42(2), 139- 142. 1989.

[15] Rawls, W.J., T.J. Gish, and D.L. Brakensiek. Physical Properties and Characteristics. *Advances in Soil Science*, Volume 16. 213- 234. 1991.

[16] Rawls, W.J., Y.A. Pachepsky, J.C. Ritchie, T.M. Sobecki, H. Bloodworth. Effect of soil organic carbon on soil water retention. *Geoderma* 116. 61–76. 2003.

[17] Regonda, S. K., B. Rajagopalan, M. Clark, and E. Zagona. A multimodel ensemble forecast framework: Application to spring seasonal flows in the Gunnison River Basin, *Water Resour. Res*. 42, W09404. 1-14. 2006.

[18] Saxton, K. E. and W. J. Rawls. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Sci. Soc. Am. J*. 70:1569–1578. 2006.

[19] Sciuto, G. and B. Diekkruger. Influence of Soil Heterogeneity and Spatial Discretization on Catchment Water Balance Modeling. *Vadose Zone J*. 9:955–969. 2010.

[20] Tietje, Olaf and Volker Hennings. Accuracy of the saturated hydraulic conductivity prediction by pedo-transfer functions compared to the variability within FAO textural classes. *Geoderma* 69. 71-84. 1996.

[21] Van Genuchten, M. Th., F. J. Leij and S. R. Yates. *The RETC code for quantifying the hydraulic functions of unsaturated soils.* U. S. Environmental protection agency, Ada, Oklahoma. EPA/600/2-91/065. p 83. 1991.

[22] Wosten, H., A. Nemes and M. Acutis. Functional evaluation of pedotransfer functions. Pachepsky, Y. A., and W. J. Rawls (Eds). *Development of Pedotransfer Functions in Soil Hydrology*. Developments in Soil Science 30. Elsevier, Amsterdam. 390-394. 2004