ISSN (Print) : 0974-6846
Indian Journal of Science and Technology, Vol 9(2), DOI: 10.17485/ijst/2016/v9i2/86356, January 2016 ISSN (Online) : 0974-5645

Simulation Model for Predicting the Effects of Changes in Land Use on Watershed Hydrology

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Abstract

Objective: Land use changes, driven by increase in population, and expansion of commercial interest, are happening in all parts of the world. Reductions in forest area were reported to have resulted in hydrologic changes and consequential disasters. Paired catchment studies were conducted in many parts of the world to assess the effects of changes in forest area on watershed hydrology, but the results from those studies were grounded to the locations of the study and could not be generalized and transferred to other locations. Such studies took very long time, and huge cost, despite many uncontrolled parameters between the catchments. **Methods**: Conceptual models have been recommended to develop scenarios for changes in land use. A newly developed Watershed Processes Simulation (WAPROS) model has been used for simulating scenarios for land use changes. The study design included: partial conversion of 0, 20, 40 and 60% of agriculture area to impervious area; 0, 20, 40 and 60% of forest area to agriculture; 0, 20, 40 and 60% of forest area to fallow; and complete conversion to forest, and to agriculture area. The reduction and expansion of forest area could be considered as equivalent to deforestation, and afforestation experiments. **Findings:** The capability of WAPROS model to generate all elemental processes was useful to interpret and link the causes and effects of changes. The scenario results showed: +60% change from forest to impervious area caused –100%, –28.5% and +4.6% changes in overland flow, baseflow and channel flow; +60% change from forest to agriculture caused +6%, –3.9%, and +7.8% changes in infiltration, peak flow and minimum flow. Comparison of 100% conversion to forest, and to agriculture showed higher channel flow and peak flow for full forest, and higher infiltration and evapotranspiration for full agriculture area. **Applications/Improvements:** The results supported studies that rejected the sponge theory attributed to forests.

Keywords: Agriculture, Forest, Impervious Area, Land Use Changes, Modeling, Scenarios

1. Introduction

Land use changes are unavoidable and growing with the population of mankind. These changes cause consequential changes in hydrologic processes. When such hydrologic changes upset the natural equilibrium to the extent of impairing the environment, the conscious authority steps in and initiate both curative and preventive actions[1]. The causes for such impairment should be assessed unambiguously, as the land use decision naturally becomes a water resource decision[1], involving different partisan groups, often with parochial interests[2–5].

The specialists, who have been entrusted with the study on environmental consequences, cannot conduct field experiments to study the effect of land use changes, for an immediate answer. The land use experiments are constrained by nature, size, duration, cost, controllability, objections and litigations, besides being irreversible. If the answer to the question, or the result of the experiment, turns out to be negative, it is not going to be easy to reconstruct or reverse the whole.

Nevertheless such field experiments have been tried over a century, as paired catchment studies, in the USA[6], the UK[7], the USSR[8], Africa[9], Australia[10], etc. but with

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mixed results[2]. The results from catchment experiments were also found to be contradictory[8,9,11]. Many researchers recommended supplementation of such experiment results with model studies[9,12], to aid in 'whitening of the watershed black box'[13].

Hydrologic models are being used to simulate hydrologic processes in a watershed, after satisfactory calibration and validation. The models are basically meant to substitute for the long duration and destructive experiments[14]. Good models ensure meaningful scenarios, and in turn the generation of meaningful scenarios vouch for reliability of models.

The WAPROS is a hydrologic simulation model, developed to generate hydrologic processes, with water balance component. The model is capable of simulating the lumped - elemental processes and the addition - depletion processes for water balance equations. The model is applied to Ebbanad watershed, calibrated and evaluated. The evaluation results of performance of the model and storage closure with water balance equation suggest application of the model for land use change scenario development.

The land use changes have been considered for both partial and complete conversions. Under partial area conversion[15,16], land use changes from agriculture to impervious area, from forest to agriculture use, and from other uses to lie fallow have been considered. The land use changes were applied incrementally in stages, so that series of changes for the respective scenario could be simulated and studied. Under complete area conversion[5], whole of the watershed was considered to be either under forest or under agriculture. Conversion of forest area to go fallow, and complete area conversion with full forest cover bear similarities to deforestation and afforestation scenarios. These combinations of changes in land uses were imposed on Ebbanad watershed and the corresponding changes in hydrologic processes were simulated with WAPROS model. For each of these scenario, the changes in simulated processes were studied.

2. Experimental Studies for Land Use Changes

The land use changes in the watershed, such as afforestation, deforestation, conversion from forest to urban, agricultural uses and fallowing, were studied experimentally. Many catchment experiments were conducted in different parts of the world, which relied on 'with-without' (paired catchment) and 'before-after' (time trend) techniques[17]. These experiments produced very useful findings, but with mixed results owing to regional disparities and watershed peculiarities. The plot scale experimental designs could not be adopted in the watershed scale due to large scale heterogeneities. The long period of observations[18], and the huge cost of such projects were reported as disincentives for furthering such studies[19]. Under paired catchment studies for land use changes, other factors could not be controlled[9]. The reviews and criticisms on the studies indicated the impossibility to reach generalizations or to transfer the results to other locations[13]. However, many such catchment experiments proved to be 'valuable outdoor laboratories'[20], and its results indicated useful hydrologic possibilities which could not be dismissed.

Regression techniques help to circumvent the difficulties in handling control and treatment factors[21,22]. The regression equations were fitted to the past observed data, and extrapolated to get the future data, but the method suffered from inter-dependent or auto correlated factors. Moreover, the regression method was reported to be not efficient enough[23] to handle non-linear rainfall-runoff processes, and to develop scenarios.

These difficulties pave the way for estimating the hydrologic changes through simulation modelling. Many researchers recommended use of models as the best alternative[8,24,25,32], to understand the causal relationships[12].

3. WAPROS Model and Application

WAPROS model has been specifically developed for simulating hydrologic processes in small and medium sized watersheds. It is a new lumped, deterministic hourly model developed exclusively for simulating hydrologic processes and water balance in watersheds of size from 100 to 10000 ha to suit Indian conditions. As the space and time scales objectivized for WAPROS were finer, the model was programmed to be more sensitive than that meant for a large basin and monthly simulation[15].

3.1 WAPROS Model Development

The model has been developed to simulate 15 hydrologic processes, with 10 hydrologic storages. The hydrologic processes were differentiated into additive and depletive processes and distinctions were made between lumped and elemental processes. The model simulated hydrologic storage positions and process values on hourly basis and integrated hourly data into daily data for use in watersheds where only hourly rainfall and daily channel flow data were available. The model also synthesised elemental processes into lumped processes usable for water balance. The model generated two water balance equations, closure errors for 10 storages, and water balance ratios.

3.2 Application of the Model

The model has been 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° 26' 15" N and 76° 45' 30" E. A Silt monitoring station, located in the drain point of the watershed and equipped with continuous hydrologic monitoring with logger recordings, was the data source.

3.3 Watershed Characteristics

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: area under forest: 1722 ha; area under agricultural crops including tea plantations: 1797 ha; and impervious area under rocks, habitations and roads: 63 ha. The average longitudinal slope of the watershed is 7.01 % and the average cross sectional slope is 32.52 %. The weighted average of the soil constituents are estimated as: sand: 55.01 %; silt: 17.40 %; clay: 27.59 %; organic matter: 1.45 %; and coarse fragments: 1.23 %.

3.4 Model Simulation Results

The simulated channel flows from WAPROS were compared to the observed flows and the results of evaluation, with respect to hourly and daily data were: Nash-Sutcliffe's Efficiency (NSE) = 0.8588; 0.9029; Volume Handling Efficiency (VHE) = 0.9409; 0.9409; Mean Square Error (MSE) = 0.4030; 0.2413; Ratio of RMSE to Standard Deviation of Observed flow (RSR) = 0.3758; 0.3117; and Coefficient of determination: (r^2) = 0.8623; 0.9073.

Simulation results with a coefficient of determination < 0.6 or VDE >± 10% were generally considered too poor to be acceptable. It was also recommended that both the NSE and the correlation coefficient were to be > 0.8 for an acceptable calibration for monthly streamflow[15]. In a similar study, an NSE value of 0.7 was considered as satisfactory, and 0.8 as very good for daily data. The following values of evaluation criteria have been recommended for monthly simulation data: 1. NSE: > 0.75 for very good; 0.75 – 0.65 for good and 0.65 – 0.50 for satisfactory ratings; 2. ME (Bias) (±): < 0.10 for very good; 0.10 – 0.15 for good and 0.15 – 0.25 for satisfactory ratings; and 3. RSR: < 0.50 for very good; 0.50 – 0.60 for good and 0.60 – 0.70 for satisfactory ratings. It could be seen that the performance of the model for hourly and daily data surpassed the ratings recommended for monthly data, suggesting a 'very good' rating for WAPROS model. The very good performance of the WAPROS model lends more support to develop hydrologic scenarios for changes in land use, rainfall and temperature.

4. Methodology for the Study

The study of land use change is often described as Land Use and land Cover Change (LUCC). The land cover change indicates no change in land use class but changes in vegetative species within the same class. The change of species from pine to eucalyptus under forest use, or the change from potato to cauliflower under agriculture use constitute land cover changes. Land use change is sometimes referred to as 'conversion' from one to another land use, and land cover change as 'modification' within the same land use[26]. The scenario development study covered in this paper did not consider land cover changes, and considered only land use changes.

This study considered four types of land uses, viz. forest, agriculture, impervious area and fallow area. The partial change and complete change in land uses were considered. The partial land use change permitted different types of combinations of land uses to coexist, as could be seen in a watershed. The complete change entails 100% change in land use leading to hypothetical monotype land use in the whole use in the whole watershed; it may have little practical relevance but will help in drawing some useful inferences about the pattern of changes on different hydrologic processes. As the land use changes were proposed to be grounded to reality, all the simulations were applied on Ebbanad watershed, with the calibrated WAPROS model. The values of parameters fixed during the calibration were unchanged and considered to apply to the extended scenario conditions too. The rainfall and other climate factors were kept unchanged, to get the changes owing to the land use alone.

4.1 Partial Area Conversion

Under this, only a part of the land use is proposed to be changed to another land use, and to have a better understanding about the quantum and direction of changes in hydrologic processes the land uses were changed incrementally in stages[16]. This type of incremental changes would help in understanding the trend, and in getting results for similar fractured conditions

4.1.1 Conversion of Area from Agriculture to Impervious Area

The impervious area generally indicates the area under buildings and roads due to urbanization. Sometimes rock outcrops may also constitute impervious area, which may be ignored for the present scenario study. There was 63 ha under impervious area in Ebbanad watershed during the study period. For scenario purposes, this area was added to area under agriculture, to make the initial simulation with zero area under impervious area (IMP1). Then 20% of the area is deducted from agriculture use and added to impervious area (IMP2), so that total area of the watershed is kept unchanged. This procedure is repeated at 40 and 60 % levels and designated as IMP3, and IMP4. Now four types of agriculture and impervious area based land uses (IMP) were available, for which changes in hydrologic processes were simulated. The area details of theland use changes were given in Table 1.

4.1.2 Conversion of Area from Forest to Agriculture Use

Here the existing land uses under forest and agriculture were taken as such with no change (AGFO1). Then 20% of the forest area was assumed to be converted to agricultural use; that is, 20% of the forest area was deducted from forest use and added to agricultural use (AGFO2), to maintain the total area of the watershed. This procedure was repeated at 40, and 60 % levels and designated as AGFO3, and AGFO4. Now four types of forest and agriculture area combinations were available, for which changes in hydrologic processes were simulated. During this conversion, it was assumed that the respective area would be under agricultural crops for the whole period of simulation. The cultivation of agricultural crops was considered to follow traditional method of deep ploughing and inter-cultivation practices. The soil conservation treatments like contour bunding, terracing, etc. were executed in 1218.0 ha mostly in agricultural lands, and for scenario studies this coverage was removed from simulation to get non-intervention results. The no-till or minimum tillage farming advocated in the western countries were not followed in this part of country, and not considered in this study. The area details of the land use changes were given in Table 3.

4.1.3 Conversion of Area from other uses to Lie Fallow

Fallowing is meant to let the land unused. These lands would not be under vegetation or urbanization. During the study period, there was no area under fallow in the Ebbanad watershed and this zero area under fallow was taken as FAFO1. Then 20% of the area under forest was assumed to go fallow (FAFO2), maintaining the total area unchanged. The conversion of forest land to fallow land might also interpreted as a phase of deforestation. This procedure is repeated for 40 and 60 % levels and designated as FAFO3 and FAFO4. Now four types of forest and fallow area combinations were available, for which changes in hydrologic processes were to be simulated. The area details of the land use changes were given in Table 6.

4.2 Complete Area Conversion

Under this category, the extreme cases of complete conversion, or 100% mono land use conditions were assumed[5] and hydrologic scenarios were developed. Under this scenario, the entire area of the watershed was either brought under Forest (FOR100), or Agriculture (AGR100). These changes were imposed on WAPROS model one at a time and the hydrologic changes for the respective changed land uses were simulated. The area details of the land use changes were given in Table 10.

5. Results and Discussions

The simulated changes in hydrologic processes due to changes in impervious area were given in Tables 1 and 2; the data relating to conversion of area from forest to agricultural use were given in Tables 3, 4 and 5; the changes caused by allowing the land to remain fallow were given in Tables 6, 7, 8 and 9; the hydrologic changes caused by complete conversion to forest or agriculture use were given in Table 10. The impact of land use changes on watershed hydrology were treated as different scenarios, and were discussed separately.

5.1 Conversion of Area from Agriculture to Impervious Area

From Table 1, it can be found that, as impervious area increased from 0 to 1116.0 ha, or from 0 to 31% of the total area (IMP1 to IMP4): 1. The infiltration was reduced by 7.2%; 2. The Evapotranspiration (ET) was reduced by 6.1%; 3. The channel flow was increased by 4.6%; 4. Peak flow was increased by 46.2%; 5. Minimum flow was decreased by 88.7%; 6. Median of flow was decreased by 29.4% and 7. The coefficient of variation was increased by 22.8%.

The increase in peak flow, the decrease in low flow and the increase in coefficient of variation indicated that the flow regime had changed. The decrease in median of flow accompanied by increase in mean of flow, indicated that the flow was becoming unstable, characterizing 'high becomes higher and low becomes lower' syndrome. Similar predictions had also been reported from earlier studies[21,16,12].

Table 1. Effects of change in impervious area on hydrologic processes

No.	Simulated processes	IMP1	IMP2	IMP3	IMP4
		0.0*A	0.20*A	0.40*A	0.60*A
O	LAND USE CHANGES [ha]				
1	Impervious area	0.00	372.00	744.00	1116.00
2	Forest area	1722.00	1722.00	1722.00	1722.00
3	Agricultural area	1860.00	1488.00	1116.00	744.00
4	Fallow area	0.00	0.00	0.00	0.00
5	Total area	3582.00	3582.00	3582.00	3582.00
A	PROCESS STATISTICS [mm]				
1	Total rainfall	547.39	547.39	547.39	547.39
2	Total infiltration	397.31	389.38	382.94	368.84
3	Total evapotranspiration	219.75	215.65	211.20	206.36
4	Total channel flow	263.88	267.84	272.09	276.00
B	HOURLY FLOW[m^3/s]				
1	Maximum simulated flow (peak)	10.60	11.83	13.44	15.49
2	Minimum simulated flow	0.03	0.02	0.01	0.00
3	Mean of simulated flow	1.16	1.18	1.20	1.22
4	Median of simulated flow	0.51	0.46	0.40	0.36
5	Coeff of variation ofsim flow [-]	1.41	1.48	1.58	1.73

In Table 2, the effects of change in impervious area on channel flow and its elemental processes were presented. From Table 1, it was found that the channel flow was increased by 4.6%, but the mechanism behind the increase in flow could be revealed only when the elemental processes constituting the channel flow were examined.

The percentage changes in elemental processes, as impervious area was increased from IMP1 to IMP4, were estimated and given below:

Elemental processes	IMP1-4
From overland flow	– 100%
From base flow	– 28.5%
From impervious area	α
From variable source area	– 100%
From interflow (UL)	– 14.9%
From interflow (LL)	– 37.3%
Total channel flow	+ 4.6%

As flow from impervious area was separately simulated, the overland flow includes flow from natural landscape only and excludes that from impervious area. The resulting increase in channel flow at 4.6% due to increase in impervious area was found to have been caused by increase in flow from impervious area, despite decreases in all other sources of channel flow. Had the lumped channel flow process been not broken down to the above elemental processes, the actual changes caused internally might not have been unveiled.

Table 2. Effects of change in impervious area on channel flow processes

No.	Sources of channel flow (mm)	IMP1	IMP2	IMP3	IMP4
		0.0*Ag	0.20*Ag	0.40*Ag	0.60*Ag
1	From overland flow	97.21	58.32	18.65	0.00
2	From base flow	134.60	124.80	114.63	96.18
3	From impervious area	0.00	54.02	109.58	166.89
4	From variable source area	12.77	12.90	13.06	0.00
5	From interflow (upper layer)	1.79	1.72	1.65	1.53
6	From interflow (lower layer)	16.40	14.97	13.40	10.28
7	From channel storage difference	1.11	1.11	1.12	1.12
8	Total channel flow	263.88	267.84	272.09	276.00

From the tables, it could be concluded that increases in impervious area caused decreases in infiltration and ET, which contributed to marginal increase in channel flow. The increase in impervious area reduced overland flow from natural terrain and all subterranean flow including base flow, which were more than offset by substantial flow from impervious area, increasing the channel flow. The higher values of coefficient of variation associated with increasing impervious area, indicated that channel flow behaviour turned unstable and irregular.

5.2 Conversion of Area from Forest to Agriculture use

Under this, forest area was converted as agriculture area, at 20% increment level (AGFO1 to AGFO4). The abstract details of changes in hydrologic processes due to conversion from forest to agriculture area were given in Table 3. The land use change from AGFO1 to AGFO4 increased area under agriculture, by decreasing the area under forest, maintaining the total area of the watershed.

The percentage change in estimates of hydrologic processes due to conversion of above said land use were: 1. The infiltration was increased by 6%; 2. The ET was increased by 3.9%; 3. The channel flow was decreased by 1.7%; 4. Peak flow was decreased by 3.9%; 5. Minimum flow was increased by 7.8%; 6. Median of flow was increased by 1.5% and 7. The coefficient of variation was decreased by 1.5%. The increase in low flows from forest to agriculture conversion falsifies the sponge theory ascribed to forests, conforming to the findings of other researchers[3,7].

In Table 4, the effects of change in land use from forest to agriculture, on infiltration and its elemental processes were given. It could be seen from the table that the increase in total infiltration (6%) was mainly due to more rainfall infiltration (7.6%), despite decreases in infiltrations from soil detention (27.1%), surface detention (18%), structural detention (18.9%) and overland flow (6.2%).

The relatively high percentage decreases in other infiltration processes were offset by the high volume increase in values of rainfall infiltration. The increase in rainfall infiltration in agriculture land, when compared to forest land, was due to crop cultivation practices that included deep ploughing.

The effects of change in land use from forest to agriculture, on ET and its elemental processes were given in Table 5.

The percentage changes in elemental processes related to ET, with respect to changes from AGFO1 to AGFO4, were given below (E for evaporation and T for transpiration):

E from canopy interception = –54%
E from soil detention = + 28%
E from surface detention = + 73%

Table 3. Effects of changes in land use from forest to agriculture on hydrologic processes

No.	Simulated processes	AGFO1	AGFO 2	AGFO 3	AGFO 4
		Ag	Ag+0.2F	Ag+0.4F	Ag+0.6F
O	LAND USE CHANGES [ha]				
1	Impervious area	63.00	63.00	63.00	63.00
2	Forest area	1722.00	1377.60	1033.20	688.80
3	Agricultural area	1797.00	2141.40	2485.80	2830.20
4	Fallow area	0.00	0.00	0.00	0.00
5	Total area	3582.00	3582.00	3582.00	3582.00
A	PROCESS STATISTICS [mm]				
1	Total rainfall	547.39	547.39	547.39	547.39
2	Total infiltration	395.92	404.45	412.39	419.60
3	Total evapotranspiration	219.09	222.43	225.33	227.63
4	Total channel flow	264.52	262.74	261.25	260.02
B	HOURLY FLOW [m^3/s]				
1	Maximum simulated flow	10.71	10.59	10.45	10.30
2	Minimum simulated flow	0.03	0.03	0.03	0.03
3	Mean of Simulated Flow	1.17	1.16	1.15	1.15
4	Median of Simulated Flow	0.50	0.50	0.51	0.51
5	Coeff of variation ofsim flow [-]	1.42	1.41	1.41	1.40

Table 4. Effects of changes in land use from forest to agriculture on infiltration

No.	Sources of infiltration, mm	AGFO1	AGFO 2	AGFO 3	AGFO 4
		Ag	Ag+0.2F	Ag+0.4F	Ag+0.6F
1	From direct rainfall	367.60	377.34	386.65	395.35
2	From soil detention	0.42	0.38	0.34	0.31
3	From surface detention	11.30	10.67	9.95	9.16
4	From structural detention	7.15	6.79	6.36	5.93
5	From overland flow	9.45	9.28	9.08	8.86
6	Total infiltration	395.92	404.45	412.39	419.60

Table 5. Effects of changes in land use from forest to agriculture on evapotranspiration

No.	Sources of evapotranspiration, mm	AGFO1	AGFO 2	AGFO 3	AGFO 4
		Ag	Ag+0.2F	Ag+0.4F	Ag+0.6F
1	Evaporation from canopy interception	17.37	14.69	11.43	8.06
2	Evaporation from soil detention	0.39	0.43	0.47	0.50
3	Evaporation from surface detention	2.46	3.00	3.61	4.25
4	Evaporation from structural detention	1.36	1.66	2.01	2.35
5	Evaporation from soil upper layer	28.02	32.12	37.06	42.51
6	Transpiration from upper layer	76.65	80.61	84.13	87.10
7	Transpiration from lower layer	92.85	89.92	86.62	82.86
8	Total evapotranspiration	219.09	222.43	225.33	227.63

E from structural detention = + 73%
E from soil upper layer = + 52%
T from upper layer = + 14%
T from lower layer = – 11%
Total ET = + 3.9%.

The reduction of transpiration from lower layer was directly attributed to shrinkage of deep roots due to reduction of area under forest. The reduction in forest area had resulted in reductions of interception losses and transpiration from lower layer, as expected. The total ET was normally expected to decrease after reduction in forest area, but the simulation pointed to the contrary. The major contributions to the increase in ET were from evaporation and transpiration from soil upper layer, typical of agricultural land use, which offset other decreases. The former may be attributed to more soil exposure to radiation and drying due to smaller leaf area index, and the latter due to more number of young plants and roots, and more infiltration caused by ploughing.

From the above it could be concluded that conversion of forest land to agriculture use might also result in marginal increase in infiltration and ET, causing marginal decrease in channel flow. These values supported the studies from large basins of former Soviet Union[20] and Kumaun Himalaya[27].

The tillage practices integral with agricultural cultivation promoted more infiltration and thus more low flows and base flow, suggesting agricultural use a viable option for forestry, so far as it remains rain-fed or unirrigated. The caveat was the impact of reduction in forest area on accelerated soil erosion and agricultural pollution, which were not dealt in this study.

5.3 Conversion of Area from other uses to Lie Fallow

Under this scenario, the area under forest was incrementally reduced by 20% and the area under fallow was increased from 0.0 to 1033.20 hectares (FAFO1 to FAFO4). This scenario of large scale removal of forests and letting it to lie fallow was analogous to deforestation. Hence the discussions were focused more on assessing the characteristics of increase in area of fallow lands or deforested lands.

From Table 6, it could be found that decreases in infiltration and ET contributed to increase in channel

Table 6. Effects of changes in fallow area on hydrologic processes

No.	Simulated processes	FAFO1	FAFO2	FAFO3	FAFO4
		0.0*FO	0.20*FO	0.40*FO	0.60*FO
O	LAND USE CHANGES [ha]				
1	Impervious area	63.00	63.00	63.00	63.00
2	Forest area	1722.00	1377.60	1033.20	688.80
3	Agricultural area	1797.00	1797.00	1797.00	1797.00
4	Fallow area	0.00	344.40	688.80	1033.20
5	Total area	3582.00	3582.00	3582.00	3582.00
A	PROCESS STATISTICS [mm]				
1	Total rainfall	547.39	547.39	547.39	547.39
2	Total infiltration	395.92	388.42	379.42	367.42
3	Total evapotranspiration	219.09	217.69	214.81	208.30
4	Total channel flow	264.52	265.10	266.39	271.18
B	HOURLY FLOW [m^3/s]				
1	Maximum simulated flow	10.71	11.70	12.70	13.54
2	Minimum simulated flow	0.03	0.02	0.01	0.01
3	Mean of simulated flow	1.17	1.17	1.17	1.20
4	Median of simulated flow	0.50	0.43	0.39	0.39
5	Coeff of variation ofsim flow [-]	1.42	1.50	1.58	1.63

flow. The percentage change in estimates of hydrologic processes due to conversion of above said land use were: 1. The infiltration was decreased by 7.2%; 2. The ET was decreased by 4.9%; 3. The channel flow was increased by 2.5%; 4. Peak flow was increased by 26.4%; 5. Minimum flow was decreased by 71.5%; 6. Median of flow was decreased by 22.1% and 7. The coefficient of variation was increased by 14.6%.

The decrease in minimum (low) flow and increase in coefficient of variation showed unstable nature of flow and the disadvantage of going without vegetation. These results showed more similarities with previous deforestation experiments and models[28–31].

The effects of changes in land use from forest to lie fallow, on infiltration and its elemental processes were given in Table 7.

The percentage changes in elemental processes related to infiltration, with respect to changes from FAFO1 to FAFO4, were given below:

From direct rainfall	= – 8.1%
From soil detention	= – 48.2%
From surface detention	= –26.9%
From structural detention	= – 9.9%
From overland flow	= + 56.2%
Total infiltration	= – 7.2%

It could be seen that increasing the area under fallow from FAFO1 to FAFO4, increased infiltration from overland flow, but causes decreased infiltration in all other elemental processes, resulting in 7.2% reduction in total infiltration. The larger decrease in volume of infiltration from direct rainfall could not be compensated by increased infiltration from overland flow, causing overall decrease in infiltration.

Table 7. Effects of change in fallow area on infiltration

No.	Sources of infiltration, mm	FAFO1	FAFO2	FAFO3	FAFO4
		0.0*FO	0.20*FO	0.40*FO	0.60*FO
1	From direct rainfall	367.60	359.91	350.67	337.74
2	From soil detention	0.42	0.34	0.24	0.22
3	From surface detention	11.30	10.15	9.05	8.26
4	From structural detention	7.15	6.85	6.48	6.44
5	From overland flow	9.45	11.17	12.98	14.76
6	Total infiltration	395.92	388.42	379.42	367.42

The effects of bringing more area under fallow, on ET and its related elemental processes were given in Table 8.

The percentage changes in elemental processes related to ET, with respect to changes from FAFO1 to FAFO4, were given below:

E from canopy interception	= – 83.1%
E from soil detention	= + 45.2%
E from surface detention	= + 211.1%
E from structural detention	= + 267.6%
E from soil upper layer	= + 274.6%
T from upper layer	= – 44.7%
T from lower layer	= – 51.8%
Total ET	= – 1.2%.

The substantial increase in evaporation was found to be from soil upper layer, to compensate for reductions in transpiration from soil upper layer and lower layer caused by decrease in vegetation. The very small decrease in total ET could not be dismissed as insignificant, as the ET elemental processes showed very high changes. The reduction in vegetation caused reduction in transpiration, which was to some extent compensated by increases in evaporation processes. The reduction in ET could also be attributed to decrease in infiltration and lesser wetting of the soil.

Table 8. Effects of change in fallow area on evapotranspiration

No.	Sources of evapotranspiration (mm)	FAFO1	FAFO2	FAFO3	FAFO4
		0.0*FO	0.20*FO	0.40*FO	0.60*FO
1	Evaporation from interception	17.37	13.97	8.13	2.94
2	Evaporation from soil detention	0.39	0.49	0.54	0.57
3	Evap. from surface detention	2.46	4.53	6.44	7.65
4	Evap. from structural detention	1.36	2.63	4.01	5.00
5	Evaporation from soil upper layer	28.02	50.88	78.70	104.96
6	Transpiration from upper layer	76.65	67.13	55.40	42.39
7	Transpiration from lower layer	92.85	78.07	61.59	44.79
8	Total evapotranspiration	219.09	217.69	214.81	208.30

In Table 9, the effects of change in fallow area on channel flow and its elemental processes were presented.

The percentage changes in elemental processes that constitute channel flow, with respect to changes from FAFO1 to FAFO4, were given below:

From overland flow = +52.2%
From base flow = – 26.2%
From impervious area = + 5.7%
From variable source area = +3.3%
From interflow (UL) = – 23.2%
From interflow (LL) = – 40.2%
Total channel flow = + 2.5%

The increase in overland flow and decreases in base flow and interflows were typical characteristics of deforested lands that were discernible in the above analysis. Similar results were reported by other researchers[2,5,19].

From this scenario analysis, it could be concluded that increases in the area under fallow, decreased infiltration, which in turn increased in overland flow and decreased ET and all subterranean flows. The reduction in vegetation cover decreased interception losses and transpiration from soil upper and lower layers. The increase in peak flows, the decrease in low flows and the increase in coefficient of variation were also the distinctive characteristics of unstable flows attributed to deforestation.

5.4 Complete Area Conversion

Under this scenario, the entire area of the Ebbanad watershed was projected to be brought under either Forest (FOR100), or Agriculture (AGR100). The simulated hydrologic changes caused by complete conversion in land use for FOR100 and AGR100, were given in Table 10.

Table 9. Effects of changes in fallow area on channel flow

No.	Sources of channel flow, mm	FAFO1	FAFO2	FAFO3	FAFO4
		0.0*FO	0.20*FO	0.40*FO	0.60*FO
1	From overland flow	90.70	106.34	122.44	138.07
2	From base flow	132.92	119.81	107.00	98.16
3	From impervious area	9.06	9.28	9.47	9.58
4	From variable source area	12.79	13.04	13.20	13.22
5	From interflow (upper layer)	1.78	1.65	1.50	1.37
6	From interflow (lower layer)	16.16	13.87	11.66	9.66
7	From channel storage	1.11	1.11	1.12	1.12
8	Total channel flow	264.52	265.10	266.39	271.18

Table 10. Effects of change of complete conversion of land use on hydrologic processes

No.	Process details	FOR100	AGR100
O	Land use changes [ha]:		
1	Impervious area	0.00	0.00
2	Forest area	3582.00	0.00
3	Agricultural area	0.00	3582.00
4	Fallow area	0.00	0.00
5	Total area	3582.00	3582.00
A	Process statistics [mm]:		
1	Total rainfall	547.39	547.39
2	Total infiltration	345.44	432.97
3	Total evapotranspiration	196.93	228.15
4	Total channel flow	276.72	260.66
B	Hourly flow[m^3/s]:		
1	Maximum simulated flow	11.01	9.90
2	Minimum simulated flow	0.03	0.04
3	Mean of simulated flow	1.22	1.15
4	Median of simulated flow	0.52	0.51
5	Coeff of variation ofsim flow [-]	1.42	1.36
C	Sources of infiltration[mm]:		
1	From direct rainfall	312.14	409.73
2	From soil detention	0.56	0.26
3	From surface detention	13.68	8.41
4	From structural detention	8.41	5.49
5	From overland flow	10.65	9.09
6	Total infiltration	345.44	432.97
D	Sources of ET[mm]:		
1	From canopy interception	23.79	1.09
2	From soil detention	0.25	0.56
3	From surface detention	0.96	5.54
4	From structural detention	0.54	2.94
5	From soil upper layer	15.61	52.87
6	Transpiration from UL	51.27	91.40
7	Transpiration from LL	104.50	73.75
8	Total evapotranspiration	196.93	228.15
E	Sources of channel flow[mm]:		
1	From overland flow	101.38	87.70
2	From base flow	142.89	139.54
3	From impervious area	0.00	0.00
4	From variable source area	11.48	13.64
5	From interflow (UL)	1.92	1.72
6	From interflow (LL)	17.93	16.95
7	From channel storage	1.11	1.11
8	Total channel flow	276.72	260.66

As simulated values were available for both the scenarios FOR100 and AGR100, the data can be interpreted in two ways: 1. Land use change from AGR100 to FOR100, representing the change in values of FOR100 processes with respect to that of AGR100 as the base, denoted as A to F; and 2. Land use change from FOR100 to AGR100, representing the change in values of AGR100 processes with respect to that of FOR100 as the base, denoted as F to A.

When comparing the process values in FOR100 and AGR100, it could be seen that the channel flow and the peak flow were higher for FOR100, and infiltration, ET and low flows were higher for AGR100. The mean, median and coefficient of variation of flow were slightly higher for FOR100.

When the elemental processes of infiltration in the two cases were compared, it was found that infiltration from direct rainfall was lesser in FOR100 due to higher interception losses, while all other sources contribute more infiltration in FOR100. The percentage changes in elemental process values related to infiltration, with respect to one another, were given below:

Sources of infiltration	A to F	F to A
From direct rainfall	– 24%	+ 31%
From soil detention	+ 120%	– 55%
From surface detention	+ 63%	– 39%
From structural detention	+ 53%	– 35%
From overland flow	+ 17%	– 15%
Total infiltration	– 20%	+ 25%

From the above, it can be seen that infiltration from direct rainfall was lesser by 24% for FOR100 when compared to AGR100, and that the same was more by 31% for AGR100 when compared to FOR100. These differences caused total infiltration to decrease by 20% for FOR100, and the same increased by 25% for AGR100.

The lesser infiltration for FOR100 also causes decrease in ET. The percentage changes in elemental processes related to ET, with respect to one another, were given below:

Sources of ET	A to F	F to A
E from canopy interception	+ 2091%	– 95%
E from soil detention	– 54%	+ 119%
E from surface detention	– 83%	+ 476%
E from structural detention	– 82%	+ 445%
E from soil upper layer	– 70%	+ 239%
T from upper layer	– 44%	+ 78%
T from lower layer	+ 42%	– 29%
Total ET	– 14%	+ 16%

The interception and transpiration losses from soil lower layer were higher for FOR100. The evaporation and transpiration from soil upper layer were higher for AGR100 and these, along with other increases, caused total ET to increase by 16% when compared to FOR100. The pattern of changes in ET for afforestation or deforestation was still a debatable issue. The atypical changes in ET for agricultural use were fully attributed to higher infiltration due to tillage and land development measures and continuous on-farm cropping.

The total channel flow for FOR100 was higher by 6% than that for AGR100. The higher ET reduced all subterranean flow including base flow marginally for AGR100. The increase in channel flow for FOR100 was caused by more overland flow and less ET.

From the above analysis, we could conclude that FOR100 or forested land was characterized by more canopy interception, less infiltration and more overland flow and thus higher channel flow. AGR100 was characterized by more infiltration and more ET and less channel flow. When the flows were compared, more overland flow and more subterranean flows can be found in FOR100. The peak flow was higher with FOR100 and the low flows were higher with AGR100. These phenomena were unconventional and its cause was attributed to continuous cropping and intensive agricultural practices accompanied by deep ploughing, and inter-cultivation practices.

6. Conclusions

The effects of changes in land uses on hydrologic processes were studied using simulation model. The land uses were considered to change both partially and completely. Under partial area conversion, land use from agriculture to impervious area, from forest to agriculture, and from other uses to lie fallow have been considered. Under complete area conversion, whole of the watershed was considered to be either under forest or under agriculture. Partial conversion of forest area to go fallow, and complete area conversion to forest cover were analogous to deforestation and afforestation scenarios. The simulation results of this study were summarized as below:

- Increases in impervious area decreased in infiltration, soil moisture status and ET, which contributed to marginal increase in channel flow. The increase in impervious area reduced all subterranean flow including base flow, which were more than offset by substantial flow from impervious area, to increase channel flow.

- Conversion of forest land to agriculture use marginally increased infiltration and ET, decreasing channel flow. This breaks the popular myth that reduction in forest would be always accompanied by high peak flow and more channel flow.
- Increases in the area under fallow decreased infiltration, which in turn increased overland flow, and decreased ET, and all subterranean flows. The increase in peak flows, the decrease in low flows and the increase in coefficient of variation were indicative of unstable flows attributed to deforestation.
- FOR100 or fully forested land was characterized by more canopy interception, less infiltration, more overland flow and thus higher channel flow. AGR100 was characterized by more infiltration, more ET and lower channel flow. The peak flow was higher with FOR100 and the low flows were higher with AGR100.

The tillage practices integral with agricultural cultivation, promote more infiltration and this causes more base flow and low flows, suggesting agricultural use as a viable option for forestry, so far as it remains rain-fed or unirrigated. The no-till or minimum tillage practices adopted for cropping in western countries may give different results. The limitations were that the impact of reduction in forest area on soil erosion and agricultural pollution were not dealt in this study.

Hence it is concluded that the changes in hydrologic processes caused by land use changes, depend also on physiographic, edaphic, geologic and vegetative characteristics of a watershed, and hence the impact of land use changes also differ from one watershed to another. Only the extreme changes in hydrologic processes due to extensive land use changes can be generalized. Hibbert's third condition that hydrologic response to forest-cover changes was 'extremely variable, and, for the most part, unpredictable'[28] is irrefutable, though ignored often.

7. References

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