Potential of Water Balance Modelling with Surface Water Pollution Considerations to Manage Ungauged Watersheds with an Emphasis on Multi User Concepts – Demonstrating an Application at a Watershed in Dampe, Sri Lanka

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ABSTRACT

Practicing integrated water resources management (IWRM) for sustainability is vital when there is multi user competition for the finite fresh water resources. In order to facilitate early decision making, it is necessary to evaluate ungauged small watersheds with simple, easy to apply but quantitative tools. This paper demonstrates the possibility of successfully applying the multiuser concept, the finite nature of water and system water balance, as a mean to overcome the surface water pollution in Dampe watershed (0.62km2), Sri Lanka. Since this watershed is ungauged, field visits, gauged data from the locality, estimates from available literature were used for a rational application of water balance to evaluate solutions for surface water pollution. The watershed runoff was calculated using a two parameter water balance model which enabled soil moisture accounting. The monthly water balance model for Dampe watershed which included multi sectoral water uses, the surface water quantity and quality at each key stream node for each sub catchment enabled the analysis of several scenarios. Remedial measures to overcome the problem and sustainable methods to preserve water for the future generation are proposed.

KEYWORDS: Integrated water resources management, Surface water pollution, two parameter water balance model, scenario analysis

1. Introduction

In Sri Lanka over the past few decades the reliance on water for domestic, industrial, hydropower and agricultural uses has been on the rise and it is often accused that discriminate and uncontrolled use is threatening the water resource availability of the country. Water becomes a resource approaching critical levels mainly because of the population explosion and two factors behind it. One factor is the increased demand for fresh water by the humans and their associated needs. Other is the pollution created by the anthropogenic activities such as domestic and industrial waste disposal, urban and rural infrastructure development, agriculture and deforestation. Having recognized that water is a limited resource, it is critical that sustainable methods of extracting, utilizing and preparing future development plans must be adopted without delay (IWMI, 2005).

Since the World Summit in Rio de Janeiro in 1992, Integrated Water Resources Management (IWRM) has been accepted as a philosophy which considers different uses of water to manage with stakeholder participation while recognizing its economic value and the role played by females (Anon., 2012).

The biggest drawback since this recognition has been the lack of practice and many are now casting doubts about this globally accepted philosophy (Biswas, 2008). A literature survey sheds light in this connection because of the void in case study application potential of IWRM principles especially in data scarce or ungauged catchments. Hence a case study was undertaken to explore the potential of applying IWRM principles in a small ungauged watershed. The expectation was to carry out a systematic, logical step by step case study to arrive at the order of magnitude of water resources situation at sub watershed levels paving the way to convince the stake-holders to embark on data collection programs to closely monitor the watersheds and confirm the results.

2. Methodology

2.1. Study Area and Data

Dampe watershed (0.62 km2) located in the Kesbewa Divisional Secretariat Division of the Colombo district, Sri Lanka (Figure 1) was the study area. It is composed of four Grama Niladari Divisions (GND s), namely, Delthara East, Madapatha, Batakettara South and Batakettara North. This ungauged water-shed consists mainly

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of residential areas, a few in-dustries, open forest areas, paddy fields and a wet-land.

Water for most residential and industrial areas is supplied by the National Water Supply and Drainage Board (NWSDB) and few use dug wells as their main source of water. Water for cultivation of paddy is extracted from the stream and the excess is released back to the same stream. Main water use sectors include water supply and sanitation, agriculture, irrigation, industries and the environment. Water related issues in the watershed were identified by conducting a reconnaissance survey including field interviews with community stakeholders of the watershed. Sur-face water pollution by effluents was identified as the most severe problem affecting the social, aquatic and terrestrial environments.

Site visits revealed that most internal drainage paths in the residential areas were polluted due to discharge of domestic wastewater.

2.2. Problem Statement

Field visit observations at the selected ungauged watershed revealed that the water at the outlet is polluted and that the stakeholders complain about deteriorating status without any meaningful action either by themselves or by the administrative authorities. Hence it is necessary to evaluate the status of water at each sub watershed and then demonstrate the possibility of status identification for better future planning.

2.3. Data for Water Usage

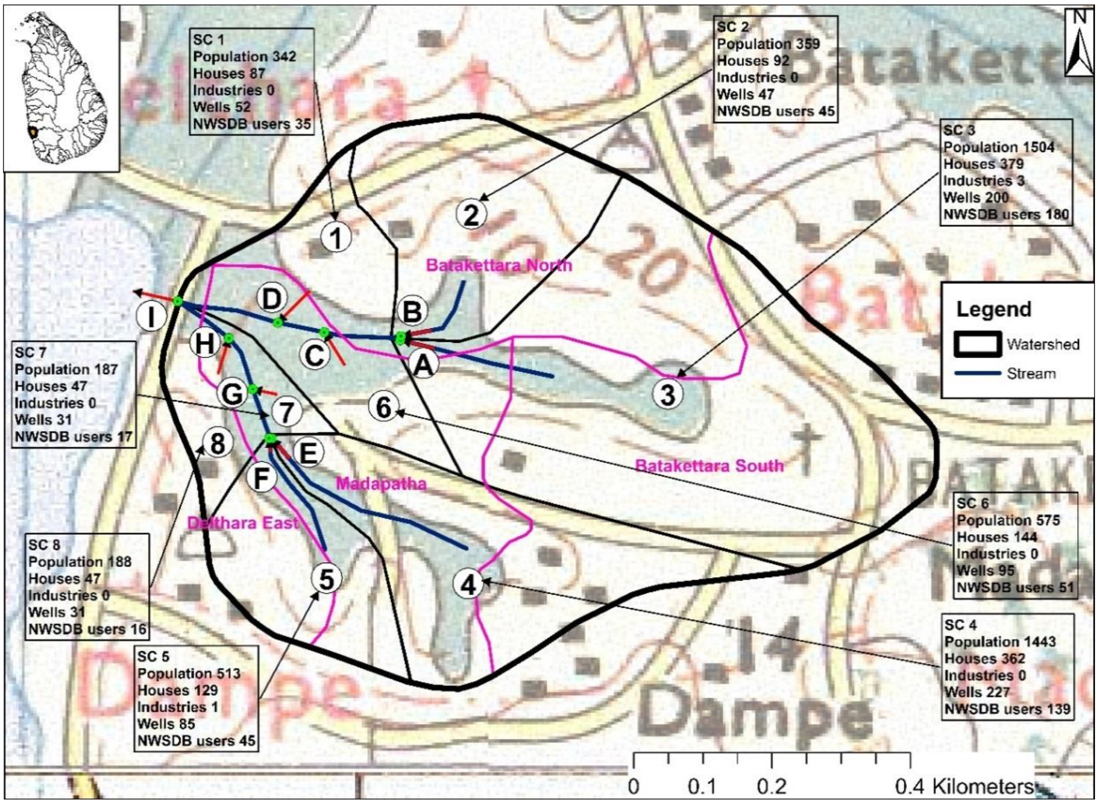


Figure 1: Location of Dampe Watershed and the Stream Schematic

Monthly rainfall data of Ratmalana gauging station from October 2011 to September 2012 was collected by Meteorological Department and average monthly evaporation data from the Irrigation Department Guidelines (Ponrajah, 1984) were available. Catchment was divided to eight sub catchments in accordance with the terrain and distribution of waterways. Vital monitoring locations to evaluate the status of water were identified by considering sub catchment inflows to the main stream (Figure 1). In the absence of detailed contours, lateral flows were assumed to contribute at the mid of each reach. Land use details from 1:50,000 maps and available information from internet were used. Land cover consisted of; open forest, built-up land, paddy, marsh, and homesteads. In order to validate field observations, area averaged runoff coefficients for each watershed were computed using land use related runoff coefficients from Chow, et al., (1988).

Population, number of housing units, number of well water users, number of NWSDB water users, in each sub catchment were obtained from the GND based reports of the Department of Census and Statistics for year 2012. Off the shelf GIS software ArcGIS was used for spatial extent computations. Crop water requirements were taken from the Irrigation Department Guidelines. Threshold dilution factors and return flows after the multiple uses were obtained from NWSDB guideline and the practices of Irrigation Department, Sri Lanka. Return flow factors of NWSDB supplied domestic water, well water, industrial water and irrigation water were taken as, 0.8, 08, 0.3 and 0.3 respectively. The threshold values of pollution were calculated considering 8 times dilution, according to the Central Environmental Authority (CEA) Guideline. The spatial and temporal resolution of data is shown in Table 1.

Table1: Spatial and Temporal Resolution of Data

Data Type	Spatial Data Resolution	Temporal Data Resolution
Rainfall	Rainfall data of Ratmalana gauging station	Monthly rainfall data from October 2011 to September 2012
Evaporation	Evaporation data of Colombo station	Average monthly evaporation data
Streamflow	Field measurements from the catchment outlet	Monthly data
Land use	1:50,000 scale	-
Population, number of housing units, number of well water users, number of NWSDB water users	GND level	Data for year 2012
Administrative divisions	1:50,000 scale	-

2.4. Water Balance

The present study focused the water balance of the surface water only. All watersheds in Sri Lanka undergo an annual hydrological cycle during which, two monsoons (southwest and northeast) occur. Hence water balance computations were carried out for a typical water year starting from October and ending in September of the following year. Rainfall for the year was taken from the average monthly data of Ratmalana Station.

As the first step, the catchment water balance was carried out by treating the entire watershed as a single lumped unit with average observed rainfall and evaporation data. The two parameter monthly water balance model (Xiong & Guo, 1998) was used for the accounting of soil moisture variation within the watershed during the water year for which the computations were carried out. The model was calibrated by using the pre-evaluated parameters for similar basins, the starting and ending watershed storage, the catchment runoff coefficients and the streamflow pattern estimated from the observations made during field visits.

After the calibration with the available data, the watershed parameters of two parameter model were assumed as representative for the sub watersheds.

In case of each watershed water abstractions, water inflow from outside, and return flow were considered for water balance considering water quality and quantity. The schematic showing the sequence of water balance computations and the critical nodes are shown in Figure 1.

The threshold dilution was considered for the separation of polluted water as beyond and within accepted levels. Environmental flow was taken to be 10% of the surface runoff.

For the verification of the model, monthly rainfall da-ta and monthly evaporation data were checked against the estimated streamflow data of the catchment. The observed flow hydrograph was drawn in order to compare the values obtained from the mathematical analysis of the water balance model with the real values. It is assumed that the soil moisture returns to the same state at the end of the water year. Hence a comparison of annual evaporation can be used as a check for inflow and outflow.

2.5. Scenario Analysis from the Developed Water Balance Model

The model was extended to analyse four scenarios, namely, for the present condition (based on data for the year 2012), for the future condition in 2025, for the evaluation of the situation in the past taking 1987 as the reference, and then for present condition with solutions. The following parameters were changed accordingly.

Mean value of annual population growth rate be-tween 1987 – 2012 had been 0.8% and 0.76% be-tween 2012 – 2014 (Anon., 2016). The decrease rates of open forest, marsh, paddy and the number of wells were taken as 1%, 0.5%, 1% and 2% respectively. The increase rates of homestead, built-up area (industries), and number of NWSDB water using houses, were taken as 2%, 1% and 2% respectively.

The effect of alternatives were analysed using the 'present condition with solutions' scenario. Evaluation of the present situation revealed a pollution level in the surface water that can be either abated by introducing more water or by reducing the pollutants reaching the surface water. Since pollution management with stakeholder consensus is far better than diversion of water from adjacent basins, the present work assumed partial reduction of pollution from each source.

The results showed that high pollution levels were due to increase of domestic and industrial wastewater discharge. As a remedial measure, it was considered that 50% of domestic wastewater and 30% of industrial wastewater should be treated by using wastewater treatment units looked after by stakeholders. These percentages were determined by using a trial and error process, such that at least the pollution level of the most critical sub catchment must be reduced by at least 10% with respect to the present scenario.

3. Results

3.1. Water Quality Balance

The calibrated two parameter models have shown the Monthly Evaporation Coefficient (c) as 0.9659 for all sub catchments. The variation of the catchment Field Capacity Coefficient (SC) for the eight sub catchments was between 300 mm and 1600 mm.

Water quality balance was analysed for all the sub catchments, and Table 1 and Figure 2 represents the results from the water quality balance analysis at the catchment outlet I. In the Table 1, inflow from sur-face runoff is the surface runoff obtained from the two parameter model. Environmental flow has been taken to be 10% of the surface runoff. Return flows from NWSDB supplied domestic water, well water, industrial water and irrigation water were summed at each month to obtain the total wastewater inflow. Then the additional water requirement for CEA acceptable level of concentration were calculated for all the wastewater sources (NWSDB supplied domestic water, well water, industrial water and irrigation water), by considering the dilution factors. After that the fresh water requirement for safe discharge has been obtained by considering 8 times dilution, and its total values are shown in Table 1. Unpolluted water quantity flowing in the stream was obtained by deducting the irrigation requirement from the inflow from surface runoff. The values of unpolluted water quantity flowing in the stream minus the fresh water requirement for safe discharge were considered to determine the critical months. The last column of Table 1 represents the polluted water quantity flowing in the stream which is the same as the total wastewater inflow column.

At present, the polluted water quantity discharged to the stream is 180,448.27 m3 per year, while the contribution from rainfall after consumption requirements is 699,553.03 m3 per year. The fresh water requirement for safe discharge at 8 times dilution is 360,896.54 m3 per year. For the months of January, February, March, June and July, the total catchment is polluted beyond the threshold limit, requiring on average an additional fresh water amount of 9124.76 m3 monthly to get the catchment back to the threshold level.

The surface water pollution levels of the sub catchments were classified into a five class system. Then the most critical sub catchment was identified. If the pollution level was below 15% it was taken as not critical, if it was between 15% – 20% it was taken as less critical, if it was between 20% - 30% it was taken as moderately critical, if it was between 30% - 40% it was taken as critical, and if it was above 40% it was taken as highly critical (Refer Figure 3).

Table 2: Water Quality Balance without Reservoir – Total Catchment at Key Point I

Month	Inflow from Surface Runoff (Thousands) (m^3)	Environmental Flow (Thousands) (m^3)	Total Wastewater In-flow (Thou-sands) (m^3)	Fresh Water Requirement for Safe Discharge (Thousands) (m^3)	Unpolluted Water Quantity Flowing in the Stream (Thousands) (m^3)	Unpolluted water quantity flowing in the stream Minus Fresh water requirement for safe discharge (Thousands) (m^3)	Polluted Water Quantity Flowing in the Stream (Thousands) (m^3)
Oct	95	10	16	32	88	56	16
Nov	132	13	13	27	132	105	13
Dec	60	6	16	31	54	22	16
Jan	38	4	16	32	30	-2	16
Feb	24	2	14	28	21	-7	14
Mar	17	2	14	28	17	-10	14
Apr	109	11	13	27	109	82	13
May	45	4	17	34	34	0	17
Jun	43	4	17	33	32	-2	17
Jul	24	2	18	36	11	-25	18
Aug	80	8	14	28	80	52	14
Sep	93	9	13	27	93	66	13
				361	700		180

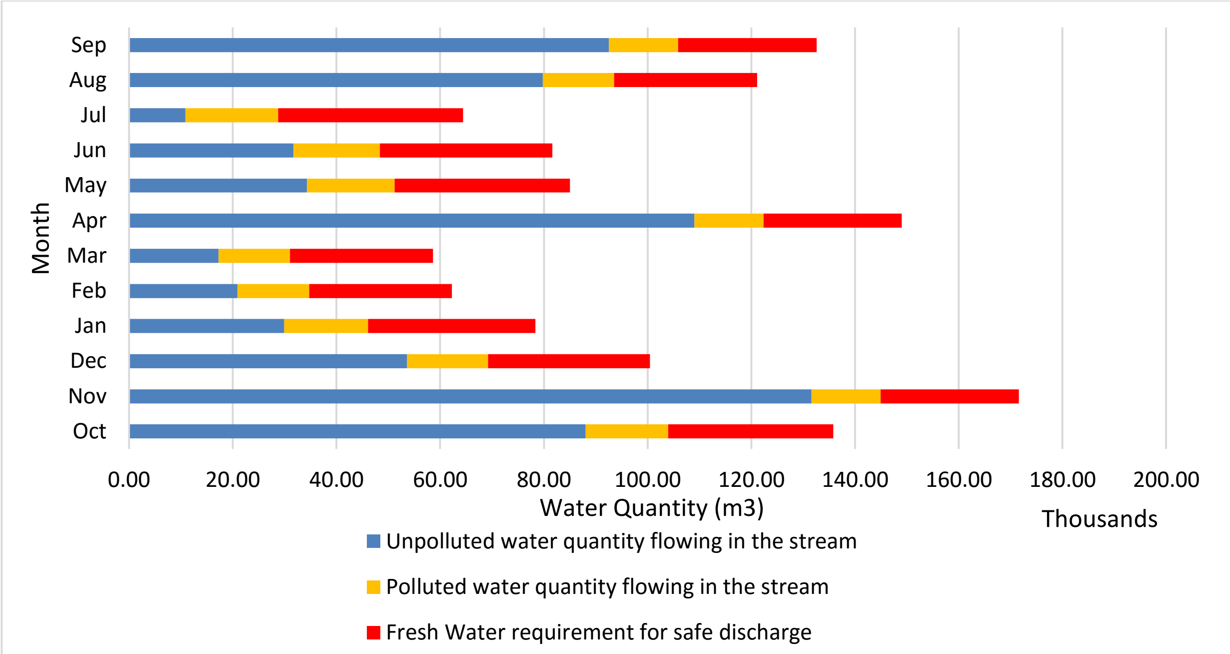
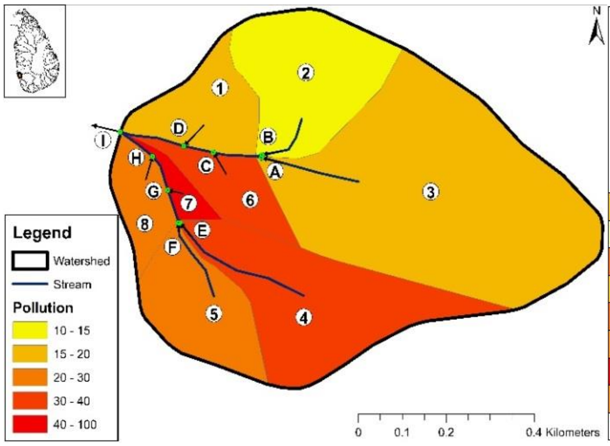


Figure 2: Water Quality Balance without Reservoir – Total Catchment at Key Point I



Key Point	Unpolluted water quantity flowing in the stream (Thousands) (m3) (Total per year)	Polluted water quantity flowing in the stream (Thousands) (m3) (Total per year)	Fresh Water requirement for safe discharge (Thousands) (m3) (Total per year)	Pollution Level [Percentage of (Polluted Water/Total Water)] (%)
SC3 at A	300	54	108	15
SC2 at B	105	12	24	10
SC6 at C	39	17	35	31
SC1 at D	55	11	22	16
SC4 at E	108	53	106	33
SC5 at F	62	17	35	22
SC7 at G	8	7	14	48
SC8 at H	22	9	18	29
TC at I	700	180	361	21

Figure 3: Five Class System Classification for the Pollution Levels

3.2. Water Quantity Balance

Water quantity balance was analysed for all the sub catchments, and discharge at every key point was found. Then the inflow and outflow at each key point was obtained. It has also been checked that the sum of total polluted water at the key point and total unpolluted water at key point equals to the discharge at that key point. Hence the water balance law has been maintained.

3.3. Future Condition

The situation of the watershed in the future, with no remedial measures taken to overcome the surface water pollution, was studied using this scenario. The year 2025 was considered and the multi sectoral water usage values were changed in the water balance model accordingly. If no further remedial action is taken, the entire catchment growing at present rate would receive a polluted water quantity equal to 216,439.45 m^3 per year. Under the same conditions the total fresh water flowing into the stream would be 706,771.45 m^3 per year. The fresh water requirement for safe discharge of pollutants would be 1,731,515.57 m^3 per year. All sub catchment pollution levels have increase in the future condition. The pollution level of the most critical sub catchment will be worsened by another 3.64% with respect to the present level. However, the sub catchment with the highest increase rises by 6.14%, pushing its status from moderately critical category to the critical category. In future, all months have become critical, except for November. (Refer Table 2).

3.4. Past Condition

In order to analyse the situation that would have been in existence 25-50 years ago, the past condition scenario was used. The values relevant to the year 1987 were used in this scenario and the multi sectoral water usage values were changed in the water balance model accordingly. The watershed was in a better condition in the past, when compared with the present situation. In the past the pollution levels were much lower. With time, the present pollution levels of all sub catchments have increased and the pollution level of the most critical sub catchment (SC7) has increased by an amount of 18.97% in these 25 years (from 1987 to 2012). (Refer Table 3).

3.5. Present Condition with Alternatives

Wastewater treatment plants should be established and the wastewater discharged from domestic usage could be diverted to these treatment facilities before releasing them into the stream. Furthermore, some of the industries could incorporate wastewater treatment plants for their industrial wastewater discharge. The present level of pollution values could be reduced to a considerable amount by the introduction of this alternative. With this solution, the pollution levels in all sub catchments have shown a decrease. The current pollution level in the most critical sub catchment (SC7) could be reduced by an amount of 12.3%. (Refer Table 4).

Table 3: Comparison of Pollution Levels – Future Scenario with respect to Present Scenario

Sub Catchment	Present condition pollution levels	Future condition pollution levels	Percentage difference in pollution levels (Increase with respect to present condition)	Pollution Level Change According to the Five Class System
	Percentage of (Polluted/Total) for this catchment (%)	Percentage of (Polluted/Total) for this catchment (%)		
SC7	47.97	51.61	3.64	still highly critical
SC4	32.96	36.72	3.77	still critical
SC6	30.70	31.59	0.88	still critical
SC8	28.59	34.73	6.14	moderately critical has become critical
SC5	21.71	24.30	2.59	still moderately critical
SC1	16.28	17.25	0.97	still less critical
SC3	15.26	18.25	2.99	still less critical
SC2	10.33	11.38	1.05	still not critical

Table 4: Comparison of Pollution Levels – Present Scenario with respect to Past Scenario

Sub Catchment	Present condition pollution levels	Past condition pollution levels	Percentage difference (with respect to past condition)	
	Percentage of (Polluted/Total) for this catchment (%)	Percentage of (Polluted/Total) for this catchment (%)		
SC7	47.97	29.00	18.97	increase with respect to past
SC4	32.96	14.99	17.96	increase with respect to past
SC6	30.70	9.55	21.15	increase with respect to past
SC8	28.59	17.92	10.68	increase with respect to past
SC5	21.71	7.97	13.74	increase with respect to past
SC1	16.28	4.09	12.19	increase with respect to past
SC3	15.26	4.00	11.25	increase with respect to past
SC2	10.33	2.16	8.17	increase with respect to past

Table 5: Comparison of Pollution Levels – Present Condition with Alternatives Scenario with respect to Present Scenario

Sub Catchment	Present condition pollution levels	Present with Alternatives condition pollution levels	Percentage difference of pollution (with respect to present condition)	
	Percentage of (Polluted/Total) for this catchment (%)	Percentage of (Polluted/Total) for this catchment (%)		
SC7	47.97	35.66	12.30	decrease with respect to present
SC4	32.96	22.24	10.72	decrease with respect to present
SC6	30.70	18.14	12.57	decrease with respect to present
SC8	28.59	21.50	7.09	decrease with respect to present
SC5	21.71	13.31	8.40	decrease with respect to present
SC1	16.28	8.86	7.42	decrease with respect to present
SC3	15.26	8.74	6.52	decrease with respect to present
SC2	10.33	5.45	4.89	decrease with respect to present

4. Discussion

There are difficulties in carrying out a water balance under data scare situations. If measured streamflow data were available for a longer period, those data could have been used for the verification of the results. In this study, monthly rainfall data and monthly evaporation data were checked against the streamflow data (estimated from the field measurements) of the catchment. Further, the average runoff coefficient obtained from the two parameter model was compared with the area averaged runoff coefficient which was calculated using the values given by Chow, et al., (1988). Since this watershed is ungauged, field visits, gauged data from the locality, estimates from available literature were used for a rational application of water balance to evaluate solutions for surface water pollution.

This study reveals a simple method of estimating planning level water quantity and water quality, with the advantage of performing a study of this order of magnitude and then identifying troubled areas. Then a detailed data collection program could be initiated for those areas.

According to the results of this study, the most critical sub watershed is SC 7 which needs urgent attention by stakeholders. (Refer Figure 3). The priority order of sub watersheds that needs attention are; SC 7, SC 4, SC 6, SC 8, SC 5, SC 1, SC 3 and SC 2.

Due to the increasing population with time, the water usage values will also increase. The domestic and industrial water demand will be increased along with the increase in population and number of industries in the future. This will result in an increase in the wastewater discharge in the watershed. In addition to that, continuation of the removal of the forest cover and transferring them into urban areas, in order to facilitate and cater for the increasing demand in human needs would be inevitable in the future. Marsh and paddy area land will also be reclaimed. Decrease in the forest area and increase in the urban area will result in an increase in the value of the runoff coefficient. This increase in the runoff coefficient has resulted in increasing the surface runoff in the future. However, this increase in the surface runoff would not be enough to dilute the high pollution levels.

Several solutions for management of water in a watershed could be identified by the results of this study. The irrigation requirement of water could be optimized if better crop management procedures are introduced to the watershed, such as cultivating crops which need lesser amounts of water, in the dry periods of the year. The monitoring of the water quality and quantity of Dampe watershed should be done monthly and the developed monthly water balance model could be used to aid the monitoring process. The key points A, B, C, D, E, F, G and I, could be used as surveillance points for the monitoring of water quality as well as quantity. By this method the sources of pollution could be identified easily. Then the problem could be isolated and solutions could be implemented to that particular pollution source. Water quantity flowing in the stream should also be measured and it could be checked for the availability of the minimum amount of water that should be there in main canal for the threshold dilution. Level gauges can be used to measure the discharges at key points. If the water quantity or quality is not up to the required level, remedial actions (such as wastewater treatment plants) for the source of that problem could be implemented. In addition, the irrigation canal system and the drainage canal system, along with the other related hydraulic structures, have to be maintained in proper condition and should be checked for necessary repairs every three to four months.

5. Conclusion

Surface water pollution by effluents was identified as the most severe problem affecting the social, aquatic and terrestrial environments of Dampe watershed. Site visits revealed that most internal drainage paths in the residential areas were polluted due to discharge of domestic wastewater. From this study, a comprehensive solution for the surface water pollution in this watershed was identified by analysing the watershed using a water balance model, and by considering Integrated Water Resources Management principles. The study demonstrates the possibility of successfully applying the multiuser concept, the finite nature of water and system water balance, as a mean to overcome the surface water pollution in Dampe watershed.

Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment. Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or groundwater aquifer.

In this watershed, due to the increasing population with time, the water usage values will also increase. More wells will be dug and the extraction rates from the wells will also increase. Since water is a finite resource, that will cause a decrease in the groundwater storage with time. Furthermore, the increasing demand of water for human needs will cause an increase in the wastewater discharge of this watershed.

Water development and management should be based on a participatory approach, involving users, planners and policymakers at all levels. The participatory approach involves raising awareness of the importance of water among policy-makers and the general public. The decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects.

All water management decisions about this watershed should be taken by a committee comprised of all water use stakeholders. Ideas of all water users have to be considered in order to do a proper water resources management. The support of all stakeholders is required in the implementing stage of those decisions. Without a combined support from all users, it would be very difficult to manage the water resources in an efficient manner.

Women play a central part in the provision, management and safeguarding of water. The role of women as providers and users of water and guardians of the living environment should be reflected in institutional arrangements.

Water has an economic value in all its competing uses and should be recognized as an economic good. It is a basic right of all human beings to have access to clean water and sanitation at an affordable price. Failure to recognize the full value of water has led to wasteful and environmentally damaging uses of the resource. Treating water as an economic good is an important mean for decision making on the allocation of water.

By implementing suitable measures to overcome the water related issues that have been encountered and by managing the utilization of water in a sustainable manner, satisfactory changes that would contribute to the preservation of this valuable resource in a more pragmatic way, could be expected.

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