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Projecting Turbidity Levels in Future River Flow: A Mathematical Modelling Approach

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Abstract: Climate and land use change impacts on river flow were evaluated in this study with emphasis placed on turbidity. Turbidity levels for the year 2020 were projected for Gin River, one of the prime sources of drinking water in Southern Sri Lanka. Future land use in the Gin catchment was predicted using a GIS based statistical regression approach. Regional Climate Modelling system generated the future rainfall for the SRES A2 and SRES A1B emission scenarios. Streamflow simulations were carried out using a distributed hydrologic model, and turbidity values were determined using rating curve based relationship developed between river discharge and TSS (Total Suspended Solid) concentration followed by Turbidity-TSS linear regression correlation.

Increased turbidity levels are clearly evident under the SRES A2 scenario, following more pronounced increased streamflows. Projected 75th percentile monthly turbidity values in year 2020 are expected to increase during May to November compared to the baseline, andin certain months, about 100%increase is noted. 60% of the time, year 2020 turbidity levels have indicated exceedance of the water quality standards set for the potable water as well the inland waters of Sri Lanka, which would lead to exert extra challenge on future drinking water production in Southern region of Sri Lanka.

Keywords: Climate change, Land use change, Hydrologic modelling, Streamflow, Turbidity

1. Introduction

Land use composition variation and climate change impacts on quantity and quality of river flows have gained significant attention in watershed hydrology. There is abundant evidence from observational records and climate projection studies that water resources are vulnerable and have the potential to be strongly impacted by climate change [1]. According to IPCC AR4 [2], freshwater availability in Central, South, East and Southeast Asia, particularly in large river basins, is projected to decrease by year 2050. Also it has been shown in several studies that, many non-climatic drivers including land use change bring in variety of impacts on freshwater resources both in quantity and quality [3].

Hydrological and sediment load responses to combined effect of climate change and land use change in humid tropical region remain less explored. Yet, environmental change in this region is supposed to alter the precipitation regime and other aspects of the hydrological cycle [4]. Hence studies in humid tropical watersheds are crucial to understand flow regime changes and consequent effects on river water quality.

Water quality is a function of chemical, physical, and biological characteristics, but is a value-laden term because it implies quality in relation to some standard. Stream water quality, however, also will be affected by streamflow volumes, affecting both concentrations and total loads [5].Turbidity is an important indicator of the quality of water. Thus, monitoring turbidity levels to meet water quality standards is vital to prevent adverse effects on human health and aquatic life, and to enhance aesthetic and recreational values. Particularly, turbidity in drinking water can interfere with disinfection and provide a medium for microbial growth. Turbidity and streamflow are related because streamflow can affect suspension of the sediment and related constituents causing turbidity [6].

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According to Sri Lanka's policy frame work, targets have been set to achieve 94% safe drinking water supply by year 2015 and 100% by year 2020 [7]. Identifying plausible impacts on future river water quality is vital in the context of drinking water production in achieving the set targets, despite the facts of increasing population pressure and declining water quality and quantity owing to various anthropogenic activities and natural processes.

The aim of this study is to evaluate the impacts on future river waterquality, subsequent to future flow regime alterations in a typical watershed in the wet zone of Sri Lanka. Riverwater quality assessment in the study is done in terms of turbidity. The study site is the Gin River basin (Figure 1) and turbidity levels are determined in Gin River flow at Baddegama (6°11'23" N, 80°11'53" E), intake point to the water treatment plant. Gin River is the most important water source to cover the drinking water supply requirement in the Galle district in Southern Sri Lanka. Recent studies exhibited degradation trend of water quality in Gin River as well significant change in land use in Gin catchment [8,9]. Lack of previous impact studies to assess similar environmental changes in humid tropical catchments including the Gin catchment makes this modelling effort important.

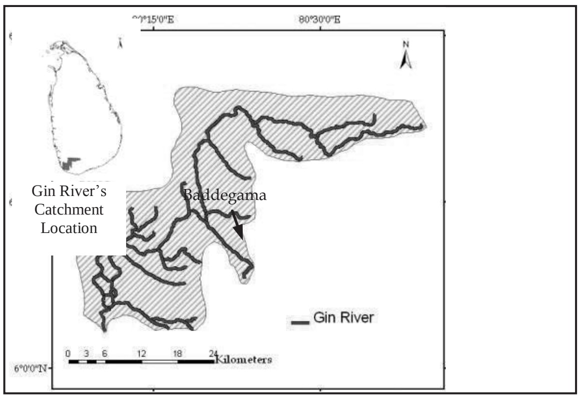

Figure 1- Gin River, its catchment location, and Baddegama river gauging station.

2. Study Area

Gin River originates from the Gongala Mountains and flows to the Indian Ocean at Ginthota. Climate conditions in the catchment are influenced by the monsoon, which has two seasons each year, Northeast Monsoon between November and February, and Southwest Monsoon between May and September followed by the inter-monsoon rains during the remaining months of the year. Rainfall increases from downstream to upstream of the catchment. In the downstream, annual rainfall is less than 2500 mm, while it is above 3500 mm in the upstream.

Gin catchment's land is mainly used for natural and plantation forest, agriculture and settlements. Cultivations include paddy and export-oriented crops such as tea, rubber, and cinnamon. Catchment lies approximately between 80°08" E to 80°40" E and 6°04" N to 6°30" N, covering 932 km² and encompassing four districts namely Galle, Matara, Kalutara, and Rathnapura. Nearly 83% of the catchment area belongs to the Galle district and district's water supply system mainly depends on the water resources in Gin River basin.

3. Data and Analysis

3.1 Climate (Precipitation) Change

Year 2020 rainfall was estimated from the PRECIS run using HadRM3P, 25 km x 25 km resolution Regional Climate Modeling (RCM) system developed by the UK Met Office Hadley Centre. Hadley Centre RCM had been successfully applied to simulate climate in the Indian subcontinent region [10]. In projecting year 2020 rainfall for the Gin catchment, two experiments were run by the UK Met Office Hadley Centre covering SRES A2 scenario and SRES A1B scenario.

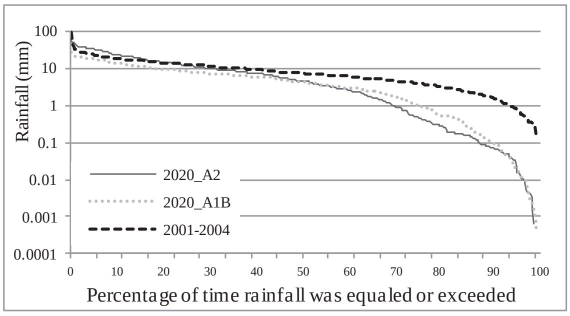

Figure 2- Rainfall vs. percentage of time rainfall was equalled or exceeded.

This study used a scaling method that considered daily patterns of rainfall change simulated by the RCM to estimate climate change impacted precipitation over the Gin catchment [11,12]. In the daily scaling method, ranked daily rainfall differences between RCM and baseline (2001-2004) were expressed as ratios relative to the baseline rainfall and these ratios were then used to scale 30 years historical catchment rainfall to produce year 2020 rainfall.

Compared to 2001-2004, magnitude of the total annual rainfall in year 2020 is expected to decrease on average by about 8% and 40% under the SRES A2 and SRES A1B, respectively, with a standard deviation of 174 mm between the scenarios. Occurrence of high intense rainfall events (between the 95th and 100th percentile) is more pronounced under the SRES A2 (Figure 2).

3.2 Change in Catchment Land Use

The study employed a spatially explicit land use change analysis across the Gin catchment in projecting year 2020 catchment land use.

By reclassifying the available land use types in the catchment, five major land use types; 'forest', 'paddy cultivation', 'other cultivation', 'homestead/ garden', and 'other', have been identified to represent the catchment land use better. 'Other cultivation' category includes export-oriented crops; tea, rubber and cinnamon. 'Other' category basically includes water bodies.

Land use demand

Future land use demand was quantitatively determined using population forecast along with growth ratio; the ratio of developed land growth to population growth [13].

$$A_2 = A_1 \left\{1 + R\left(\frac{(P_2 - P_1)}{P_1}\right)\right\} \qquad (1)$$

where, A_2 and A_1 are future and current area of considered land use type (km^2), respectively; P_2 and P_1 are future and current population, respectively; and R is the growth ratio, the ratio between growth rate of considered land use type between 1983 and 1999 (%) and population growth rate (%).

Past and present population of the area and the average annual population growth rates were obtained from the census of 1981 and 2011 [14]. Future population up to year 2020 was determined according to the 'standard' rate of growth of population, Sri Lanka [15].

Probability maps

The relative probability of occurrence of a certain land use type at a particular location was defined using binary logistic regression approach influenced by socioeconomic, proximity and biophysical driving factors (Table 1).

The probability of a certain grid cell to be devoted to a land use type is given by;

$$log\left(\frac{P_{i,u}}{1-P_{i,u}}\right) = \beta_{0,u} + \beta_{1,u}X_{1,i} + \beta_{2,u}X_{2,i} + .. + \beta_{n,u}X_{n,i} \qquad (2)$$

where, $P_{i,u}$ is the probability of grid cell i for the occurrence of the considered land use type u; β isthe regression coefficient; and X is the driving factor [16].

Allocation of land use change

Allocation of land use change was made in an iterative procedure given the probability maps, spatial policies and conversion elasticities in combination with the actual land use map in 1983 and the demand for the different land use types (Figure 3) [16]. Spatial policies are employed to indicate the areas where the land use changes are restricted through policies or tenure status. The conversion elasticity is related to the reversibility of land use change.

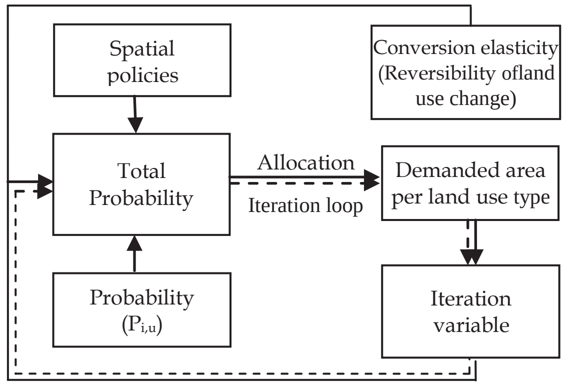

Figure 3 - Schematic representation of the iterative procedure for land use change allocation in CLUE-S modelling framework [16].

Validation of logistic regression analysis was tested using the Relative Operating Characteristic (ROC) analysis.ROCvalues range between 0.5 and 1; 0.5 for completely random and 1 for the perfect fit, respectively. Comparatively high ROC test statistics (ranging between 0.62 and 0.87) indicated that spatial distribution of all land use types were reasonably explained by the selected driving factors.

Observed land use map in 1999 was used in validating the predictions. By means of correlation matrix, 1999 projected land use data were evaluated as a percentage of locations predicted correctly. Result of validation showed that the agreement between the observed and projected land use in 1999 was quite reasonable. Overall, the percentage of total pixels being correctly projected ranged from 58% to 72%.

Table 1 - Land use change driving factors.

Type	Driving factor	Description
Socioeconomic	Population density	Population density (persons/km^2)
Proximity	Distance to nearest river	Direct distance to nearest river (m)
	Distance to nearest road	Direct distance to nearest road (m)
Biophysical	Altitude	Elevation above the Mean Sea Level (m)
	Slope	Slope (based on 1km DEM)
	Soil texture	Sandy clay loam soil, Clay loam soil, and Clay soil

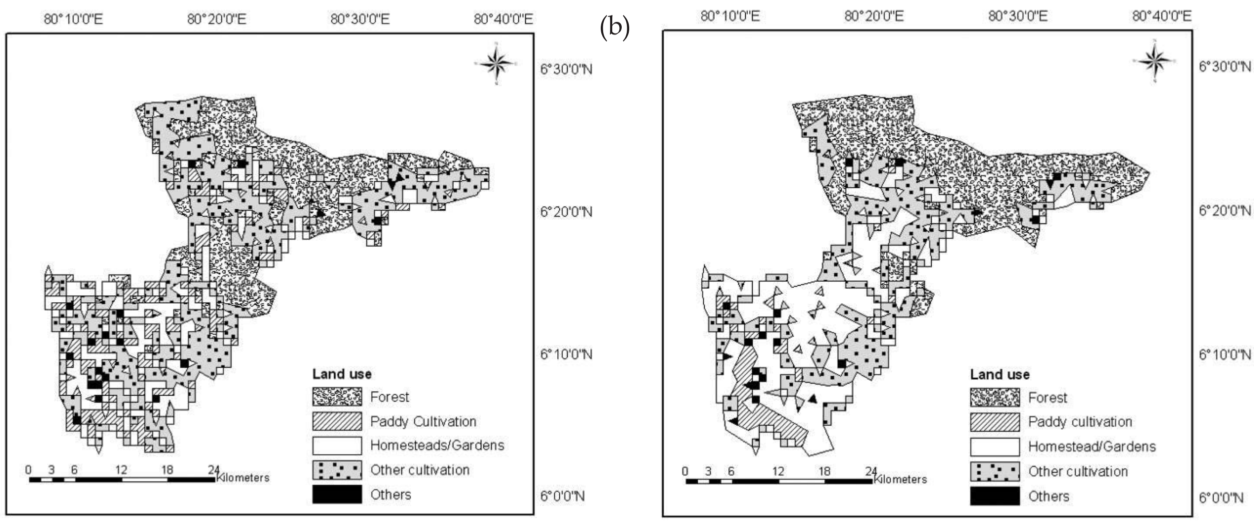

Figure 4 - Observed and projected land use.
(a) 1983 observed land use (b) Year 2020 projected land use.

Year 2020 catchment land use

Year 2020 land use projection for the Gin catchment envisaged a predominant replacement of cultivated areas in 1983 by forest and homestead/garden (Figure 4). From 1983 to 2020, drop of cultivated areas from 51% to 34% is observed. Area covered by the homestead/garden is expected to rise from 18% in 1983 to 32% in 2020. This principally reflects the rapid expansion of homestead/garden to keep pace with population growth. According to Wickramaarachchi et al.[9], Gin catchment's land use change can be summarized over the past thirty years as a result of change in agricultural practices and increase in population. Moreover, the land use change trends projected in this study are consistent with the changing trends in homestead/garden and cultivated areas between early 80's and mid 90's, in Galle, as presented in the ADB report[17].

3.3 Hydrologic Modelling

University of Yamanashi Distributed Hydrological Model (YHyM) with block wise use of TOPMODEL and Muskingum Cunge method (BTOPMC) was applied in quantifying the impacts of climate and land use change on the river flow regime. YHyM/BTOPMC has already been successfully applied to many basins, large to small, temperate to tropical, around the world [18, 19].

In the YHyM, runoff is generated based on the TOPMODEL concept [20] and flow routing is carried out using the Muskingum Cunge method [21]. The hydrological processes in a grid cell in the BTOP model are illustrated in Figure 5[19].

The runoff from a grid cell to the local schematic stream reach is the sum of saturation excess overland flow (q_{of}) and groundwater discharge (q_b) per unit length of contour line;

$$q_{of}(i,t) = \{S_{uz}(i,t) - SD(i,t)\} \qquad (3)$$

where, S_{uz} is the unsaturated zone storage; and SD is the saturation deficit for the i^{th} grid cell at time t.

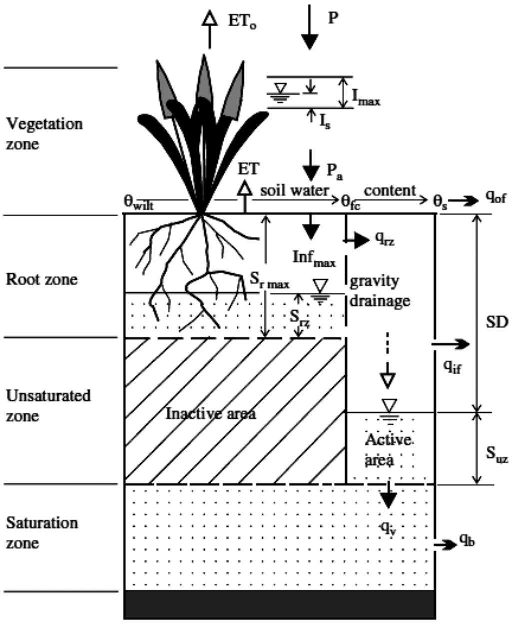

Figure 5 - Runoff generation in a grid cell in the BTOP model (the vertical profile).

In this diagram, $P$is the gross rainfall, $ET_0$is the interception evaporation, I_{max} is the interception storage capacity, $I_s$is the interception state, Inf_{max} is the infiltration capacity, $P_a$is the net rainfall on the land surface, ET is the actual evapotranspiration, $S_{rmax}$is the storage capacity of the root zone, $S_{rz}$is the soil moisture state in root zone, SD is soil moisture deficit in unsaturated zone, $S_{uz}$is the soil moisture state in unsaturated zone, $q_{of}$is the overland runoff, $q_{if}$is the saturation excess runoff, $q_v$is the groundwater recharge, and $q_b$is groundwater release. θ_{wilt}, θ_{fc}, $\theta_s$are soil water contents at wilting point, field capacity and saturation, respectively.

$$q_b(i,t) = T_0(i)\exp\left(\frac{-SD(i,t)}{m(k)}\right)\tan\beta_i \qquad (4)$$

where, SD indicates the saturation deficit;T_0 is the transmissivity; and $m(k)$ is the discharge decay factor in sub basin k.

The generated overland flow and groundwater flow of each cell are added to the stream and then routed to the basin outlet.

Model calibration and validation

Daily streamflow data from 1997 to 2001 and from 2002 to 2006 were used for calibratingand validating the model, respectively. Model performance was evaluated by the Nash-Sutcliffe Efficiency (E) and the volume ratio of total simulated discharge to total observed discharge (V_r) (Table 2).

$$E = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs_i} - Q_{sim_i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs_i} - \overline{Q_{obs}}\right)^2} \qquad (5)$$

$$V_r = \frac{\sum_{i=1}^{n} Q_{sim_i}}{\sum_{i=1}^{n} Q_{obs_i}} \qquad (6)$$

where, Q_{obs_i} is the observed discharge;Q_{sim_i} is the simulated discharge;$\overline{Q_{obs}}$ is the average observed discharge; and n is the number of time steps.

Table 2 - HyM/BTOPMC model performance.

	Calibration		Validation	
	Baddegama	Tawalama	Baddegama	Tawalama
E %	67.63	53.75	62.73	48.31
Vr%	93.15	105.50	84.94	104.24

Nash-Sutcliffe efficiency values ranging between 48% and 67% indicated acceptable level of model performance. Measured and YHyM/BTOPMC simulated streamflow showed a good agreement and overall, the model was able to adequately simulate the major hydrological characteristics in Gin catchment including runoff volume, evapotranspiration and soil moisture states of the catchment.

3.4 Turbidity-Total Suspended Solid (TSS) Correlation

Turbidity measurements are theoretically well correlated to suspended solid concentration because turbidity represents a measure of water clarity that is directly influenced by suspended solids. Hence turbidity based estimation models have been identified as effective tools for generating suspended solid concentration data [22]. Usually, turbidity-TSS relationships have been reported on site by site basis.

A direct correlation between turbidity and suspended solid concentration has been documented in many studies conducted around the world [23, 24]. In Sri Lankan context, turbidity-TSS concentration relation has been quantified through linear regression analysis study carried out recently in Gin River at Baddegama (6°11'23" N, 80°11'53" E) [25]. In the above study, the linear regression model developed between turbidity and TSS concentration (Equation 7) showed highly significant ($p < 0.0001$) strong positive correlation ($R^2 = 0.98$) and strongly suggested that turbidity is a suitable monitoring parameter for TSS.

$Y = 1.0457X$ (7)

where, Y is the TSS concentration (mg/l); and X is the Turbidity (Nephelometric Turbidity Units).

3.5 TSS Load-Discharge Model Development

In general, total mass loading over an arbitrary time period, τ, is given by;

$$L_\tau = \int_0^\tau QC\,dt \quad (8)$$

where, C is the concentration; L_τ is the total load; Q is the instantaneous streamflow; and t is the time.

Accurate estimation of constituent loads in streams is crucial for many applications, including identifying sources of nutrient loads in the catchments and assessing trends in the loads [26, 27]. LOADEST, Load-discharge rating curve [28], a computer programme developed by the United States Geological Survey (USGS) was used in this study to develop multiple regression model and estimate daily loads of suspended solids. Time series streamflow data and constituent concentrations are used in the LOADEST to develop and calibrate a regression model that describes constituent loads in terms of various functions of streamflow and time. LOADEST has been extensively applied to estimate constituent loads in rivers around the world [29, 30].

Time series of TSS concentration observations and corresponding streamflow observations at Baddegama were used in developing and calibrating the regression model using adjusted maximum likelihood estimation (AMLE) method. AMLE method is contingent upon the fact that model residuals are normally distributed. Linearity of the normal probability plot constructed, suggested that the residuals follow a normal distribution. The regression model developed for TSS (Equation 9) showed higher coefficient of determination (R^2=0.85) reflecting a strong relationship between the estimated and measured TSS loads.

$$Ln(L) = 10.88 + 1.69\,LnQ - 0.08\,LnQ^2 + 0.03\,Sin(2\pi T) + 0.30\,Cos(2\pi T) - 0.02\,T + 0.02\,T^2 \quad (9)$$

where, L is the constituent load; Q is the streamflow; R^2 is the coefficient of determination for the regression model; LnQ= Ln(streamflow) - center of Ln(streamflow); T= decimal time - center of decimal time.

Explanatory variables are centered to eliminate the co-linearity.

Relationships are considered to be significant at $p < 0.05$.

4. Results and Discussion

4.1 Integrated Impact of Climate Change and Land Use Change on year 2020 Streamflow

By driving the calibrated and validated YHyM/BTOPMC with RCM generated rainfall and projected land use in the Gin catchment, year 2020 daily streamflow at Baddegama was generated. Figure 6 shows year 2020 streamflow hydrographs for the SRES A2 and SRES A1B scenarios, as simulated by the YHyM/BTOPMC. Moreover, the hydrological response to the two forcing SRES scenarios as simulated by the YHyM/BTOPMC is illustrated using the flow duration curves (Figure 7). Increased peak flow (largely due to rainfall generated runoff) is more pronounced for the SRES A2 scenario compared to the baseline 2001-2004, as a result of increased extreme rainfall events in future. According to the simulated annual water balance, evapotranspiration, ground water recharge and base flow are expected to slightly decrease under both scenarios owing to decreased future rainfall and substantial replacement of catchment's pervious areas in future. Year 2020 total annual flow volume is predicted to increase for the SRES A2 scenario by 4% and decrease for the SRES A1B scenario by 50% compared to 2001-2004.

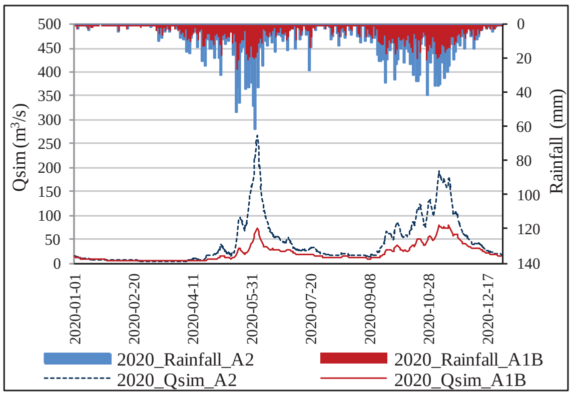

Figure 6 - Year 2020 streamflow hydrographs

Qsim – Simulated streamflow

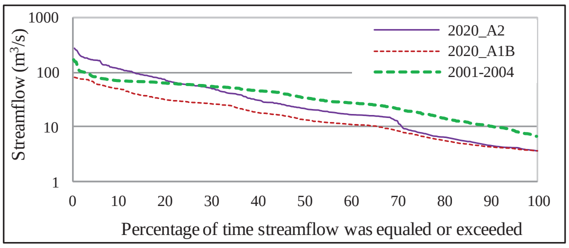

Figure 7 - Flow duration curves: Year 2020 and 2001-2004

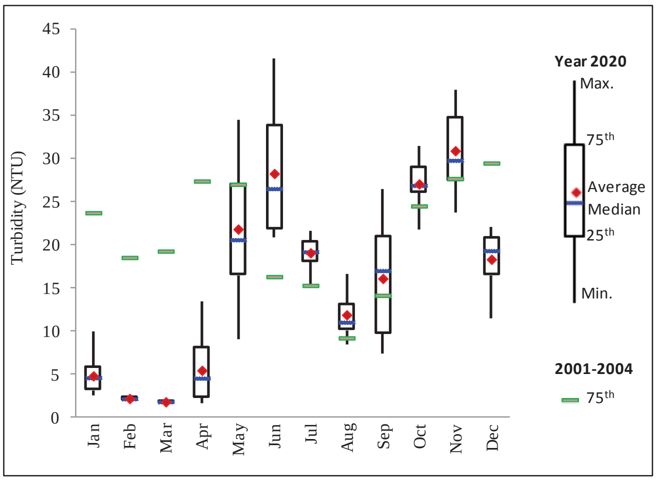

Figure 8 - Monthly turbidity (Year 2020 and 2001-2004).

- Maximum, minimum, average, median, 25th percentile and75th percentile turbidity values are shown for year 2020
- 75th percentile turbidity value is shown for 2001-2004
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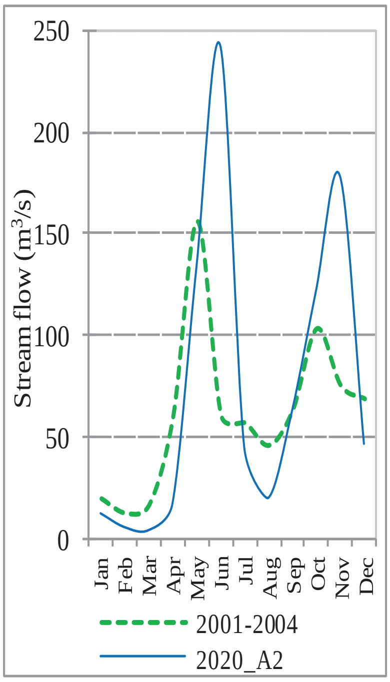

Figure 9 - 90th Percentile of monthly streamflow.

Though this study included future projections for both SRES A2 and SRES A1B scenarios, in most of the climate adaptation studies carried out, it has been identified that the most matching scenario for Sri Lankan conditions is SRES A2. This is further explained by De Silva et al.[31]. According to Figure 7, flows with high magnitudes are expected to occur under SRES A2 scenario and it is understood that generation of sediments and pollutant loads are directly related to extreme runoff events. Thus the present study opted to consider turbidity levels in future river flow regime for only SRES A2 scenario at Baddegama (6°11'23" N, 80°11'53" E), intake point to the drinking water treatment plant.

4.2 Projected Changes in Turbidity

Year 2020 TSS loads were modelled on daily basis using the TSS load-discharge model developed**.** Using the linear regression equation developed (Equation 7), corresponding turbidity values were derived.TSS is a pollutant that responds to flushing more than dilution within a catchment and therefore, higher river discharge will mostly facilitate greater erosion and transportation of the pollutant compared to dilution. Response of TSS to climate and land use changes had demonstrated that, higher the precipitation level, larger the concentration of TSS in a catchment [32, 33]. In this study, following the linear relation between TSS and turbidity, elevated levels of turbidity have been noted following the increased river discharge resulted by increased rainfall events. Thus, the response of turbidity to river flow regime changes have predicted considerably higher turbidity values in most of the months in year 2020 compared to 2001-2004, while remaining months demonstrate decrease.

Year 2020 monthly turbidity values (75th percentile) show an increase during May to November, compared to 2001-2004 (Figure 8). The height of the peak is remarkably increased in June 2020, and the projected increase in turbidity is 107% compared to the baseline. Turbidity increase predicted between May and November 2020 is 6.5 NTU per month, on average. These elevated turbidity levels are clearly evident during the months of increased streamflow (Figure 9).

4.3 Comparison of Turbidity Values with the Water Quality Standards

Turbidity vs. streamflow exceedance probability shows the range of fluctuation of turbidity in year 2020 during different flow regimes in comparison to the water quality standards (Figure 10). It appears that, 60% of the time, turbidity levels have indicated exceedance of the water quality standards set for the potable water [34] as well the inland waters [35] of Sri Lanka. These indicate that the projected turbidity levels subsequent to flow regime alterations caused by the anticipated climate and land use change, appear to be more prominent at intermediate to highest streamflows. Exceedances are greatest during the highest flows. It will be challenging to deal with the year 2020 turbidity levels projected to occur during the highest flows (>110 m3/s), requiring more than 90% remarkable reductions to comply with the water quality standards.

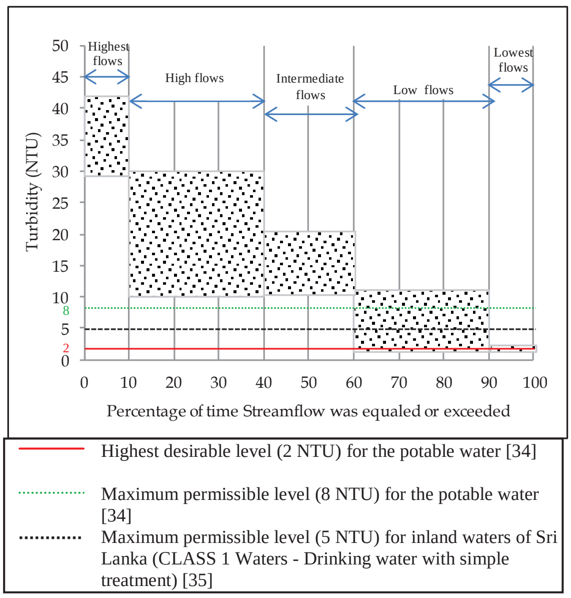

Figure 10 - Turbidity vs. streamflow exceedance probability.
Highest flows > 110 m^3/s; High flows > 30 m^3/s; Intermediate flows > 17 m^3/s; Low flows > 4.5 m^3/s; Lowest flows > 3.7 m^3/s

Despite the fact that this study considered a single RCM and two SRES emission scenarios, future change in hydro-climatological variables needs to be projected based on outputs from several different climate models operating under a variety of scenarios. Taking into account the climate projection uncertainty and modelling uncertainties, the predicted impacts on the hydrological processes and constituent estimates in the Gin catchment should be considered as trends and order of magnitudes rather than exact predictions.

5. Conclusions

This research provides important insight into possible alterations in turbidity levels in Gin River, the primary drinking water source in Southern region of Sri Lanka, following variations in future river flow under projected land use and climate change. Study revealed that fluctuations of constituents have been much more strongly related to streamflow changes, thus year 2020 flow regime alterations under SRES A2 will greatly elevate the turbidity levels in the Gin River compared to the water quality criteria. Remarkable increase in turbidity levels during the months of June and November in year 2020 would require significant reductions to comply with the drinking water quality standards, which would lead to exert extra pressure on future drinking water production in Southern region of Sri Lanka. Understanding on these excessive amounts of constituents anticipated in future river water might be useful for water managers and planners to adjust operations accordingly at the water treatment plants. Moreover, findings of the study could be vital for Sri Lanka's water resources planning efforts aiming to achieve 100% safe drinking water supply by year 2020. However, the results presented in this study should be viewed as trends and order of magnitudes rather than exact predictions, considering the uncertainties associated with future climate projections and modeling approaches adopted.

The tools and methods used in this study could be effectively applied in carrying out impact studies in similar catchments.

Fully assessing the direct impacts of climate and land use change on river water quality is beyond the scope of this study. Further researches to determine such direct impacts are suggested using a more physically based modelling approach.

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