An Assessment of Constituent Loads in Gin River at Baddegama, Sri Lanka

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ABSTRACT:
Both natural and anthropogenic factors can have impact on water resources including threats to drinking water supply systems. Current rapid development activities in the Southern region of Sri Lanka owing to substantial land use change, believe to be induced some impacts on the quality of water in the Gin river, which is the main source of drinking water supply for the Galle city area. So far no attempt has been made to study the prevailing concentrations and constituent loads in the Gin river water to establish baseline levels. Concentration and constituent loads in the Gin river at Baddegama gauging station, having catchment area of 780 km^2 were modeled in the study using LOADEST (Load Estimator). LOADEST software developed by the United States Geological Survey (USGS) for estimating constituent loads in rivers uses a rating curve which is constructed based on the observed relationship between constituent concentrations and stream flow in estimating the loads. Constituents considered in this study included Chloride, Total alkalinity, Total residue, Total hardness, Calcium, and Total iron. For each constituent, samples were collected monthly from 2001 to 2009 at Baddegama were used in conjunction with the observed daily stream flow data at Baddegama to calibrate the regression model.
Daily, monthly, and annual loads of constituents were estimated and the regression models of constituent loads showed higher coefficients of determination (R^2) values indicating strong relation between estimated and measured constituent loads. The estimated average daily loads of Chloride, Total alkalinity, Total residue, Total hardness, Calcium, and Total iron with 95% confidence interval were 104.2, 110.0, 125.7, 100.9, 61.1, and 11.6 tons per day, respectively. Estimated loads were having substantial temporal variation and generally peaked in May and October, coinciding with high flows. Except for Total Iron, for all the other constituents, estimated maximum constituent concentrations were much less than the allowable limits cited in the water quality standards for potable water and inland waters of Sri Lanka. Since the flow strongly affects the calculation of load, the ratio between average annual constituent load and average annual flow which terms the annual flow weighted mean concentrations (FWMC) were calculated to better assess the variations in concentration over the estimation period. Even though the estimated loads were large as a result of the dominance of flow, annual FWMC of Chloride, Total alkalinity and Total hardness were small and inversely related to load since they get diluted by high flows. In contrast, load and FWMC of Total residue, Total iron and Calcium were directly related, because their particulate matter was increased during high flows, not diluted.

1. INTRODUCTION

With the advent of industrialisation and increasing population, the range of requirements for water has increased together with greater demands for higher quality water. Over time, water requirements have emerged for drinking and personal hygiene, fisheries, agriculture, navigation for transport of goods, industrial production, cooling in fossil fuel power plants, hydropower generation, and recreational activities. The largest demands for water quantity, such as for agricultural irrigation and industrial cooling, demand the least in terms of water quality. Drinking water supplies and specialised industrial manufacturers exert the most sophisticated demands on water quality but their quantitative needs are relatively moderate. In parallel with these uses, water has been considered, since ancient times, the most suitable medium to clean, disperse, transport and dispose of wastes (UNESCO/WHO/UNEP, 1996). According to Sri Lankan context, the major intentional pressures on water resources are agriculture, urbanization and industrialisation that change land use patterns. Excessive use of agrochemicals and chemical fertilisers, release of industrial effluents, domestic waste and sewage, and dumping of solid waste into waterways cause unintentional pressures. These pressures collectively interact resulting in complex impacts on water resources. (U.N. Environment Programme, 2001). These influences of agricultural development, deforestation, and human settlement have been shown to affect river flow and availability of nutrients in river water, by several studies.

Hence estimation of concentrations and constituent loads in rivers becomes vital in the processes of assessing the loading to downstream water bodies and evaluating the long term trends of loads in river flow. This study is carried out with the aim to establish a detailed understanding on prevailing constituent loads and concentrations in Gin river at Baddegama. LOADEST, a FORTRAN based load estimation software (Runkel *et al.,* 2004) is used in this study to develop regression models and estimate daily, monthly, and annual loads of the six constituents; Chloride, Total alkalinity, Total residue, Total hardness, Calcium, and Total iron over the period 2001 - 2009.

1.1. Study Area and Background

Gin river originates from the Gongala mountains in Deniyaya having an elevation of over 1300 m and flows to the Indian Ocean at Ginthota in Galle district. Gin catchment is about 932 km^2 and the catchment area at Baddegama river gauging station (6°11'23" N, 80°11'53" E) is 780 km^2. The catchment is located approximately between longitudes 80°08" E and 80°40" E, and latitudes 6°04" N and 6°30" N and includes Galle (83% of the basin area), Matara (9% of the basin area), Rathnapura (7% of the basin area), and Kalutara (1% of the basin area) administrative districts. Rainfall pattern in the catchment is of bi-modal, falling between May and September (Southwest monsoon, which is the major rainfall season), and again between November and February (Northeast monsoon) followed by the inter-monsoon rains during the remaining months of the year. Rainfall varies with altitude with mean annual rainfall above 3500 mm in the upper reaches to less than 2500 mm in the lower reaches of the catchment. Gin river annually discharges about 1268 million cubic meters of water to sea (Survey Department of Sri Lanka, 2007).

Gin river is one of the main sources of water supply in Southern region of Sri Lanka. Galle is the capital city in Southern Sri Lanka and the city's pipe-borne water supply system depends on the water resources in Gin river basin. Due to current development activities in the southern region of Sri Lanka owing to substantial land use change, it is believed to be induced some impacts on the quality of water in the river Gin. So far no significant attempt has been made to understand the prevailing concentrations and constituent loads in the Gin river due to various reasons including comparatively high expenses related to sample collection and analysis. As one of the main drinking water supply sources in southern region of the country, there exist a vital need to understand the prevailing water quality conditions of Gin river in order to identify any changes likely to occur in the future, subsequent to various anthropogenic activities. This study is an effort to address this need by establishing detailed understanding on six constituents in Gin river at Baddegama.

2. MATERIALS AND METHODS

2.1. Constituent Concentrations and Stream Flow Data

Chloride, Total alkalinity, Total residue, Total hardness, Calcium, and Total iron are the constituents considered in this study of Gin river at Baddegama. For each constituent, concentration data of one hundred and six water samples tested monthly over the period January 2001 and November 2009 were obtained from the National Water Supply and Drainage Board (Southern), Sri Lanka. Daily stream flow data at the Baddegama gauging station for the same period were collected from the Department of Irrigation, Sri Lanka. Water quality and daily stream flow data collected are representative of the daily average concentration and the daily average flow of interest in this analysis, respectively.

2.2. Regression Model Development

LOADEST, a load-discharge rating curve for estimating constituent loads in rivers developed by the United States Geological Survey (USGS) is used in this study to develop regression models and estimate loads of the six constituents. LOADEST uses time series stream flow data and constituent concentrations to develop and calibrate a regression model that describes constituent loads in terms of various functions of stream flow and time. The calibrated model is then used to estimate constituent loads using daily stream flow observations over specified time period.

The calibration and estimation procedures within LOADEST are based on three statistical estimation methods; Adjusted Maximum Likelihood Estimation (AMLE), Maximum Likelihood Estimation (MLE), and Least Absolute Deviation (LAD). AMLE and MLE methods are appropriate when the calibration model residuals (errors) are normally distributed and AMLE is the method of choice when the calibration data set contains censored data. LAD is an alternative method to find maximum likelihood estimation when the residuals are not normally distributed. For the special case where the calibration data set is uncensored, the AMLE method converges to MLE, resulting in a minimum variance unbiased estimate of constituent loads (Cohn *et al.*, 1992). Since all the data sets used in this study were uncensored, model coefficients for the AMLE and MLE methods were identical and the AMLE was used to determine the model coefficients and estimate log load for each model. Two statistics, the Akaike Information Criterion (AIC) and the Schwarz Posterior Probability Criterion (SPPC), then were computed for the calibrated model (Judge *et al.*, 1988; Runkel *et al.,* 2004).

In this study, separate regression models were developed and calibrated for each constituent in estimating the loads. One hundred and six concentration observations were used in conjunction with corresponding observed stream flow data to develop and calibrate the regression model using AMLE, for each constituent. The model with the lowest value of the AIC was then selected for use in load estimation. The regression models developed for each constituent using LOADEST and their coefficients of determination (R^2) are shown in Table 1. Related to the constituent concentration data used for the model calibration, no pattern is observed between the stream flow data and the concentration data. Concentrations of Total iron generally followed the pattern of stream flow and tended to be higher when the stream flows were high.

Table 1. Regression models and their coefficients of determination

Constituent	Regression model	R^2 (%)
Chloride	$Ln(L) = 11.3813 + 0.9590\ LnQ - 0.0289 LnQ^2 - 0.0217T$	97.21
Total alkalinity	$Ln(L) = 11.4228 + 0.8674\ LnQ - 0.0564T$	83.68
Total residue	$Ln(L) = 11.5116 + 0.8152\ LnQ + 0.0321\ T$	74.94
Total hardness	$Ln(L) = 11.3048 + 0.9086\ LnQ - 0.0394T$	82.28
Calcium	$Ln(L) = 10.7710 + 0.9268\ LnQ - 0.1466 Sin(2\pi T) - 0.0970\ Cos(2\pi T) - 0.0715T$	75.68
Total iron	$Ln(L) = 8.6927 + 1.3672 LnQ + 0.0222\ LnQ^2 + 0.0148\ Sin(2\pi T) - 0.1358\ Cos(2\pi T) - 0.0305T + 0.0157\ T^2$	85.72

Notes:
L is the constituent load; Q is the stream flow; R^2 is the coefficient of determination for the regression model.

AMLE results are contingent upon the assumption that model residuals are normally distributed. Once the model formulation and calibration were done, AMLE residuals were examined to see whether the normality assumption was valid. Checks for normality included construction of a normal probability plot, a plot of model residuals versus their Z-scores, which should yield a normal probability plot (Helsel & Hirsch, 2002; Runkel *et al.,* 2004).The linearity of the plots suggested that the residuals follow a normal distribution (Figure 1). This linearity was supported by the Probability Plot Correlation Coefficients (PPCC) of 0.99, 0.98, 0.94, 0.99, 0.99, and 0.96 for Chloride, Total alkalinity, Total residue, Total hardness, Calcium, and Total iron, respectively. Coefficients of determination (R^2) of the regression models for constituent loads which represent fraction of the variance explained by regression are shown in Table 1. The relatively high R^2 values indicated that the models for all constituents successfully simulated the variability in constituent loads.

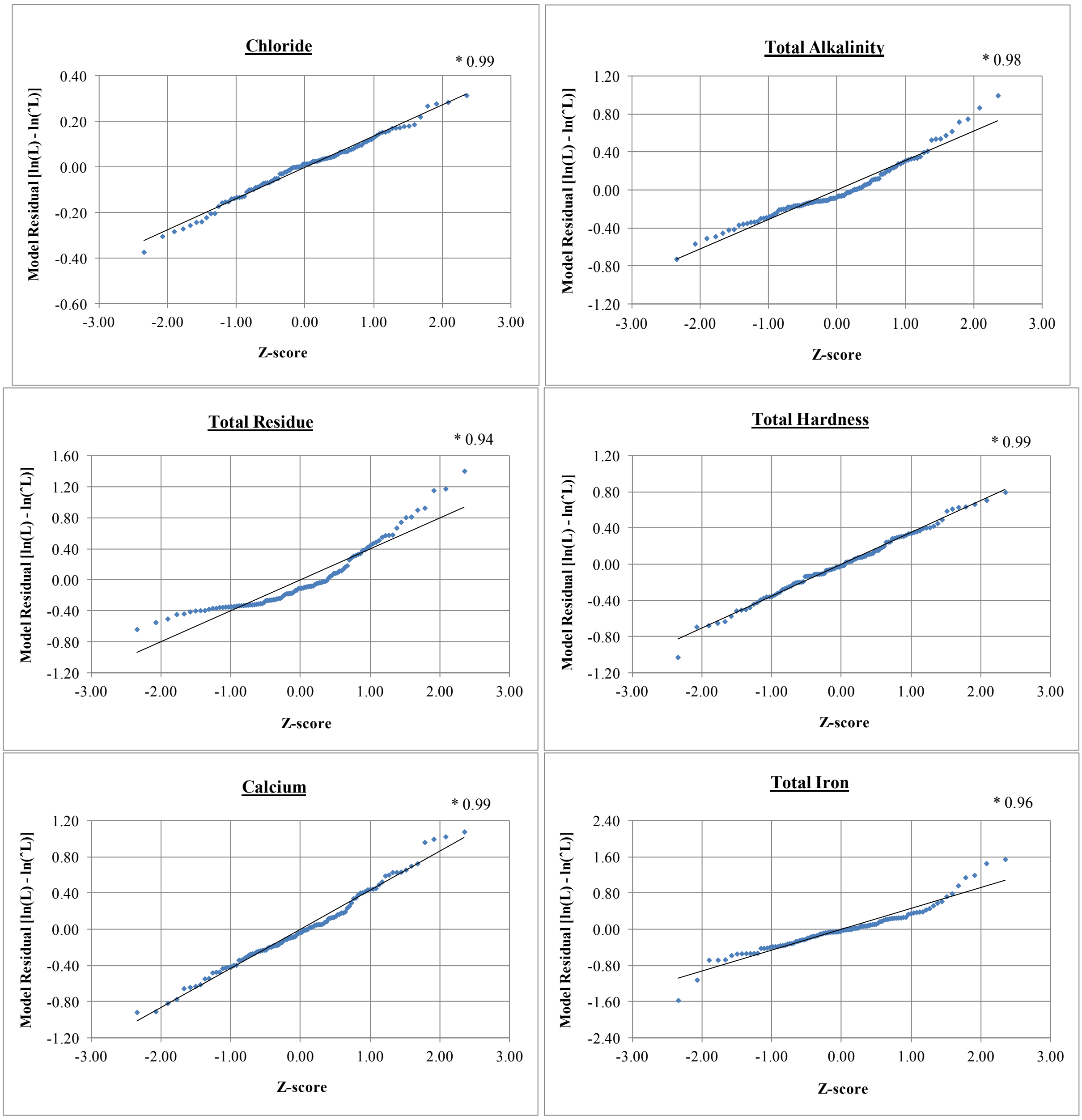

Figure 1. Normal probability plots for the model residuals of the AMLE regression
Notes: Model Residual [ln(L) - ln(ˆL)] is the difference between the observed and estimated values of log load
L is in kilograms per day
* Probability Plot Correlation Coefficient (PPCC)

3. RESULTS AND DISCUSSION

3.1. Constituent Load Estimate

Measured instantaneous loads were plotted against the estimated loads for the same day to evaluate the fitness of the regression models developed for each constituent (Figure 2). 1:1 line represents similar values for both estimated and measured. Even distribution of points across the 1:1 line for all constituents indicated that the model neither systematically overestimated nor underestimated loads. For Chloride and Total iron, more points closely clustered near the 1:1 line revealing the highest R^2 value for the regression model of Chloride followed by Total iron. The points for Total alkalinity and Total hardness were moderately scattered indicating reasonably well distributions near the 1:1 line over a wide range of loads. For Total residue and Calcium, points were more scattered revealing low R^2 values for their regression models. The scatter was very large at higher loads of Total residue since the model overestimated large loads. Similarly large scatter was observed at lower loads of Calcium since the model underestimated small loads. But for both Total residue and Calcium, models performed reasonably well at moderate loads.

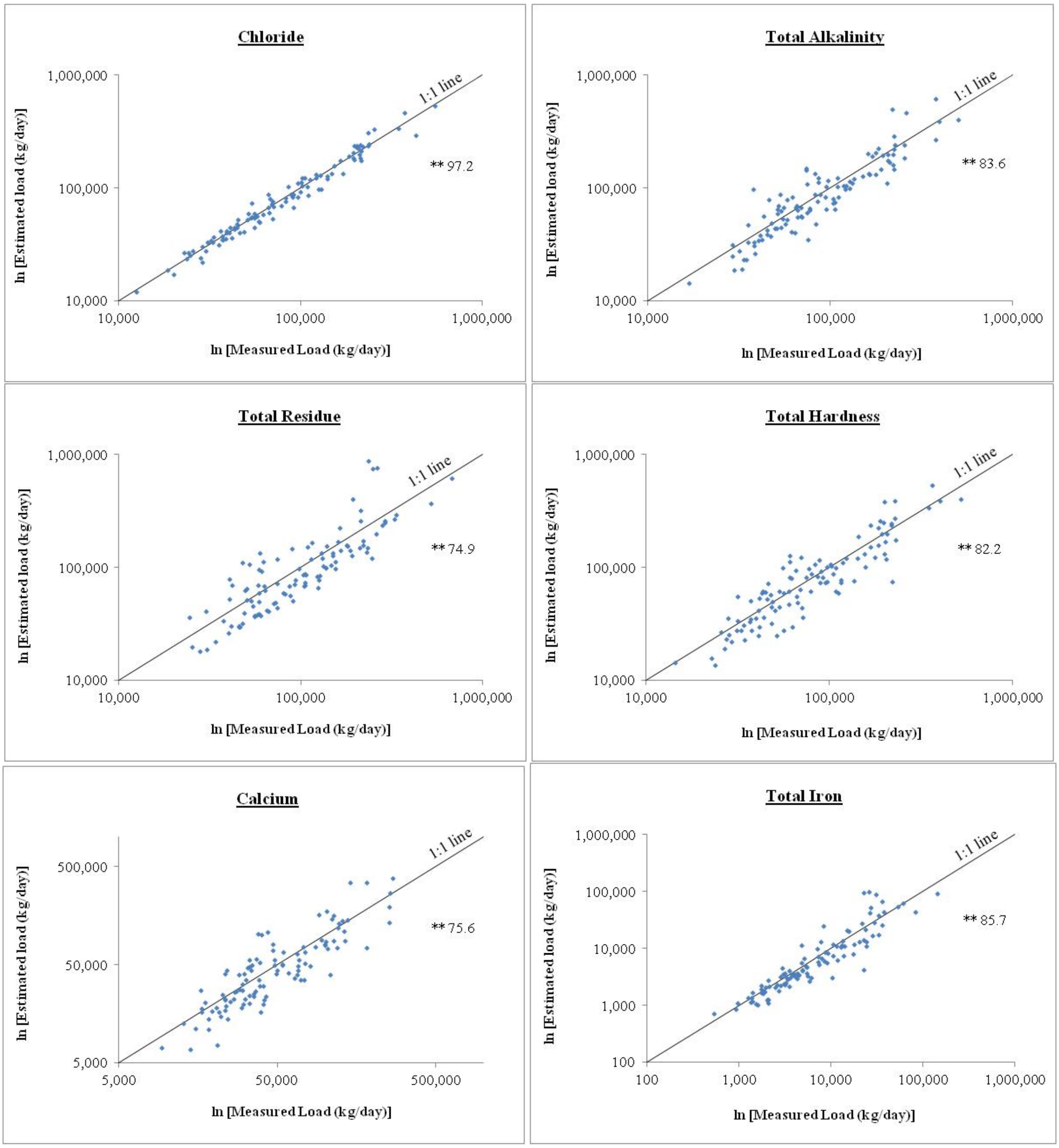

Figure 2: Relation between measured instantaneous loads and estimated loads (2001-2009)
**** C**oefficient of Determination (R^2) for the regression model

In the study, mean loads were estimated on daily, monthly and annual basis from January 2001 to December 2009 for all the constituents. Model output provided information on the errors associated with the load estimates, including upper and lower limits of the 95% confidence interval (Table 2).

Table 2. Measured and estimated loads during 2001 – 2009

Constituent	Mean measured load (tons/day)	Mean estimated load (tons/day)	Upper and Lower 95% confidence intervals of the mean estimated load (tons/day)		% Error (as a percentage of the mean measured load)		Ratio of average width of the 95% confidence interval to mean estimated load (%)
			Lower	Upper	Lower	Upper	
Chloride	106.32	104.16	100.81	107.58	5.18	1.18	6.5
Total alkalinity	112.45	110.03	102.20	118.30	9.12	5.20	14.6
Total residue	132.05	125.64	113.61	138.58	13.96	4.95	19.9
Total hardness	103.08	100.86	92.76	109.48	10.01	6.21	16.8
Calcium	63.34	61.11	54.97	67.75	13.22	6.96	20.9
Total iron	13.23	11.55	9.98	13.31	24.60	0.57	28.8

According to Table 2, the ratio of average width of the 95% confidence interval to mean estimated load of Total iron is about 29% resulting the least precise load estimates. In contrast, the highest precise is for Chloride having a ratio of 6.5%.

Daily mean concentration estimates for each constituent during 2001-2009 with maximum and minimum daily concentration estimates are shown in Figure 3.

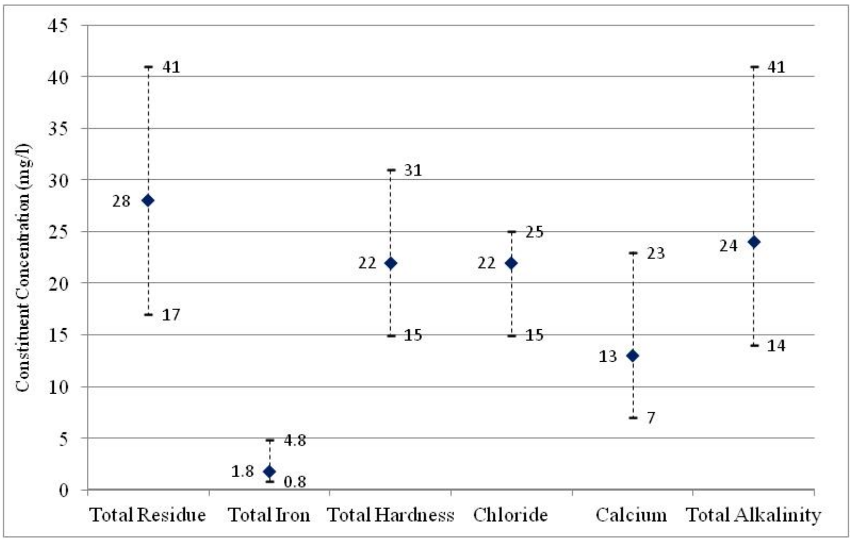

Figure 3. Daily mean concentration estimates of the Gin River at Baddegama during 2001-2009
Note: Symbols denote mean concentration; Lines represent maximum and minimum daily concentration estimates.

Table 3. Sri Lanka water quality standards

Constituent	Sri Lanka standards for potable water [a] (mg/l)	Proposed ambient water quality standards for inland waters of Sri Lanka [b] (mg/l)
Chloride	200	200
Total alkalinity	200	-
Total residue	500	-
Total hardness	250	600
Calcium	100	-
Total iron	0.3	1

Notes:
[a] Highest desirable level (SLS, 1983)
[b] Maximum permissible level for CLASS 1 Waters [Drinking water with simple treatment] (CEA, 2001)
- no specific water quality standards available

According to Figure 3 and Table 3, except for Total iron, for all the other constituents, estimated maximum constituent concentrations were much less than the highest desirable limits cited in the Sri Lanka Standards Institute for potable water (SLS, 1983) and maximum permissible limits of the proposed ambient water quality standard for inland waters of Sri Lanka by the Central Environmental Authority (CEA, 2001). Total iron concentration indicated exceedance of the water quality standards set for the potable water as well the inland waters of Sri Lanka. Intensified draining of exposed laterite soils which enriched with iron contains commonly present in the area (Herath, 1983) might be contributing to the higher concentrations of Total iron. Understanding on this excessive amount of iron presented in river water might be useful for water managers and planners to adjust operations accordingly at water treatment plants.

3.2. Variation of Constituents Loads with the River Flow

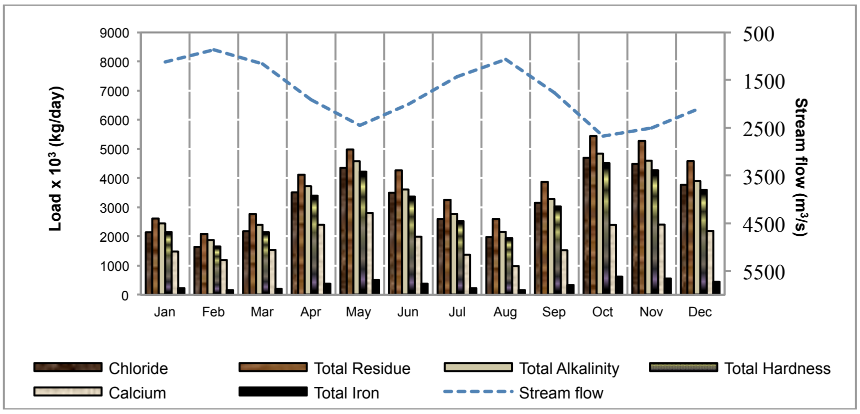

Figure 4. Mean monthly load estimates and mean monthly stream flow of Gin River at Baddegama during 2001-2009

Mean monthly load estimates and mean monthly stream flow of Gin River at Baddegama during 2001-2009 are shown in Figure 4. Estimated loads were having substantial temporal variation and generally peaked in May and October, coinciding with high flows. Highest and lowest mean monthly load estimates of Total residue were about 5,400 tons (in October) and 2,000 tons (in February), respectively exhibiting the largest monthly variations. Among all the constituents, variation of monthly load estimates was smallest for the Total iron showing the highest and lowest mean monthly load estimates of about 600 tons (in October) and 150 tons (in February), respectively. Mean monthly load estimates of Total hardness, Chloride , Calcium, and Total alkalinity ranged from about 4,500 to 1,600 tons, 4,700 to 1,600 tons, 2,800 to 950 tons, and 4,800 to 1,800 tons, respectively. Monthly average loads of total residue were consistently higher than other constituents throughout the year.

Annual load estimates of Total residue during 2001-2009 ranged from 28,872 to 63,235 tons and indicated the highest annual variation during the estimation period, which was about 4700 tons per year, on average. Annual load estimates of Total iron ranged from 3,304 to 6,213 tons during 2001-2009, exhibiting the lowest annual variation which is about 600 tons per year, on average. Estimated annual loads of Total hardness, Chloride , Calcium, and Total alkalinity during 2001-2009 ranged from 30,621 to 43,516 tons, 28,993 to 47,228 tons, 19,846 to 24,672 tons, and 36,489 to 44,605 tons, respectively.

3.3. Annual Trends in Constituent Loads

A trend is present if loads change consistently as a function of time throughout the estimation period. Statistically significant (95% confidence level) temporal trends for the constituent loads determined in the study are shown in Table 4. *p*-values shown in Table 4 indicate statistical significance of the trends and *p*-values greater than 0.05 are not statistically significant at the 95% confidence level. For Total residue, statistically significant upward temporal trend was indicated. Statistically significant downward temporal trends were observed for Chloride, Total alkalinity, Total hardness, and Calcium. Regression equation for Total iron suggested a downward temporal trend, but the trend was not statistically significant at the 95% confidence level.

Table 4. Annual trends in estimated constituent loads during 2001-2009

Constituent load	Annual trend (%)	*p*-value
Chloride	-0.0217	≈ 0
Total alkalinity,	-0.0564	≈ 0
Total residue,	0.0321	0.04
Total hardness,	-0.0394	0.003
Calcium	-0.0715	≈ 0
Total iron	-0.0305	0.09

3.4. Annual Flow Weighted Mean Concentrations

Because flow strongly affects the calculation of load, estimation of annual flow weighted concentrations facilitate the assessment of changes in concentration despite a large range in flows (Donato & MacCoy, 2005). The ratio between average annual constituent load and average annual flow, which terms the annual flow weighted mean concentrations (FWMC) were calculated in this study to better assess the variations in concentration over the estimation period. Annual FWMC for the constituents are shown in Figure 5. As the load and flow are strongly related, large estimated loads would be expected in high-flow years. Even though the estimated loads were large as a result of the dominance of flow, annual FWMC of Chloride, Total alkalinity, and Total hardness were small during high flows and inversely related to load since they get diluted by high flows. In contrast, load and FWMC of Total residue, Total iron, and Calcium were directly related, because their particulate matter was increased during high flows, not diluted.

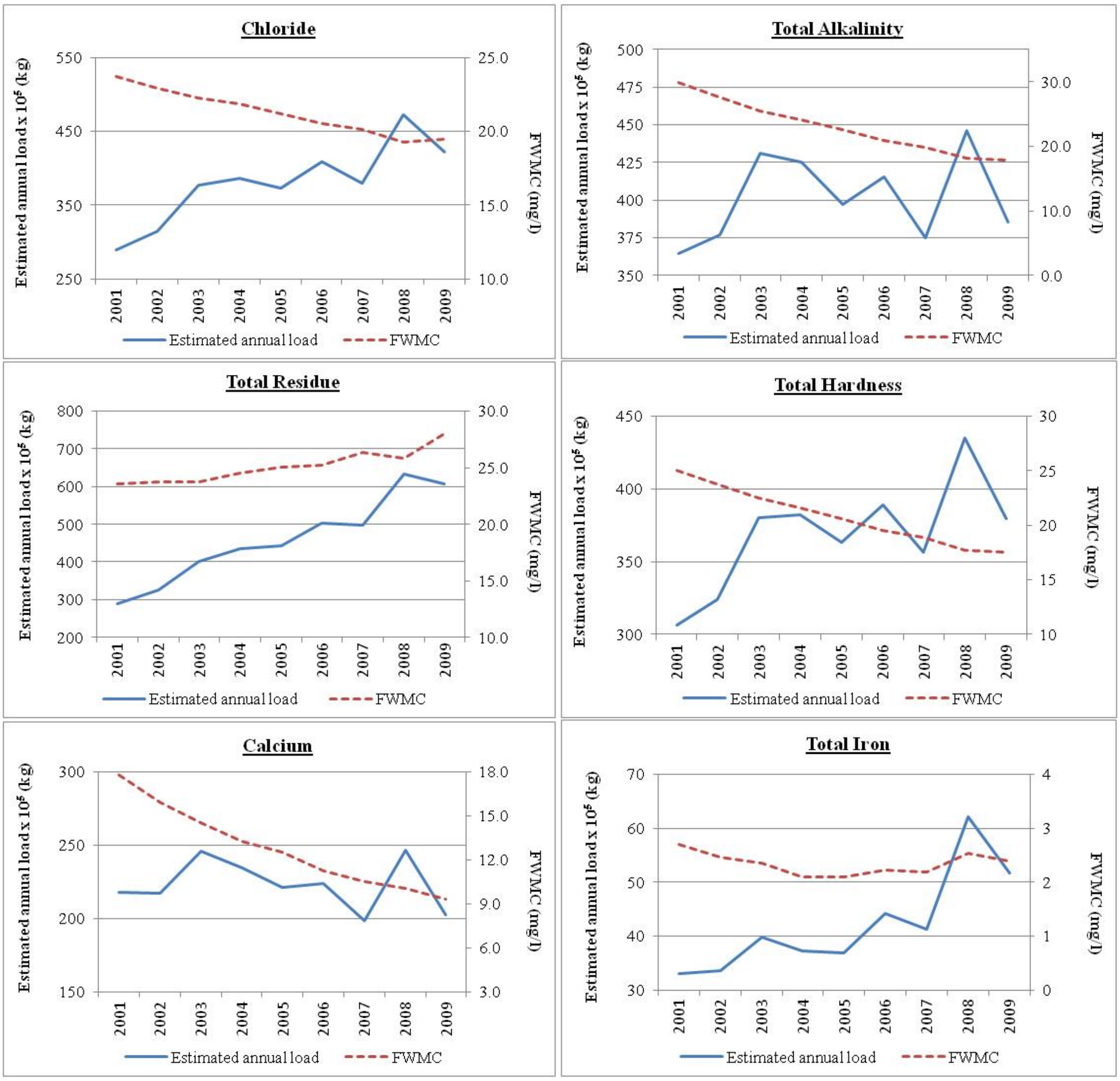

Figure 5. Annual flow weighted mean concentrations and estimated annual loads

Like in any model, quality of the results by LOADEST is determined by the quality of input data. Since water quality sampling events in input data did not represent a sufficiently wide range of stream flow conditions, load estimation output data indicate that some of the stream flow values used for estimation, exceeded the maximum stream flow values in the calibration data set. Hence some of the load estimates required extrapolation beyond the range of stream flow used for calibration. This would have been improved if constituent sampling had taken place over a wide range of flow conditions covering rising limbs, peaks, and falling limbs of a flow hydrograph at Baddegama. This would assist the model to be calibrated over a more complete range of flow conditions.

4. CONCLUSIONS

Regression models for all constituent loads showed higher coefficients of determination values reflecting overall well fitness of the models. Regression model for Total residue was the least successful in explaining variation in the data having the lowest R^2 value of 74.94. Results for Chloride were well fit on the basis of the highest R^2 value of 97.21 among all the constituents, perhaps due to the strong correspondence between Chloride and stream flow.

Monthly average loads of all constituents displayed cyclical variations coinciding with seasonal fluctuations in stream flow and peaked in May and October coinciding with high flows. Average monthly loads of Total Residue were consistently higher than other constituents throughout the year. Estimated daily average load was highest for Total Residue exhibiting 125.64 tons/day. Total Iron having daily average load estimate of 11.55 tons/day was the lowest among all the constituents. Annual load estimates varied considerably throughout the estimation period. Total residue indicated the highest annual variation during 2001-2009, which was about 4700 tons/ year, on average. Annual load estimates of Total iron during the same period exhibited lowest annual variation which is about 600 tons/ year, on average. LOADEST constituent load estimates indicated a statistically significant (95% confidence level) downward temporal trends in constituent loads of Chloride, Total alkalinity, Total hardness, and Calcium during 2001-2009. Downward temporal trend indicated for Total Iron was not statistically significant at the 95% confidence level. For Total residue, statistically significant upward trend was indicated. This increase of Total residue could be due the erosion of sediment in the channel or addition of sediment to the river from tributaries or due to both. Calculated annual FWMCs highlighted the strong interaction between the flow and particle-associated constituents and enabled concentrations to be assessed despite the variations in flow. The FWMC of Chloride, Total alkalinity, and Total hardness were small during high flows and inversely related to load because of dilution. For Total residue, Total iron, and Calcium, load and concentration were directly related because particulate matter was increased, not diluted, during high flows.

Total iron concentration indicated exceedance of the water quality standards set for the potable water as well the inland waters of Sri Lanka. For all the other constituents, estimated maximum constituent concentrations were much less than the highest desirable limits of specifications cited for the potable water and maximum permissible limits of the water quality standard for inland waters. Understanding on this excessive amount of iron presented in river water might be useful for water managers and planners to adjust operations accordingly at water treatment plants.

LOADEST Modeling results included in this study can be used to gain insight to the prevailing constituent loads and concentration conditions in the Gin River and can be used as a basis to identify any water quality changes likely to occur in future.

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