Long-term change of stream water quality as a consequence of watershed development and management

T. Kinouchi[1], K. Musiake[1]
Department of Environment System Management, Fukushima University, Japan
kinouchi@sss.fukushima-u.ac.jp

1. INTRODUCTION

The Abukuma River Watershed, one of major watersheds in Japan, is a basis of social, economical and cultural activities in the southern Tohoku region. Also, the watershed is abundant in natural environment and river landscape. Thus, the comprehensive watershed management encompassing flood control, water resources and water quality conservation is recognized as quite significant for the sustainable development of the region.

The mainstream of the Abukuma watershed runs about 240 km from the south to the north, which makes the runoff concentrate against northward moving typhoons. The spatially-averaged mean annual precipitation is about 1,400mm, which is lower than the national average. The mainstream collects flows from a great number of sub-basins, where wastewater is discharged from various sources such as industry, farmland, stock farming and domestic sectors. Due to these geographical, climatic and social conditions, the watershed has been experienced devastating floods, shortage of water resources and water quality degradation for a long time.

The Abukuma River is recognized as one of the worst quality stream among major watersheds located in the Tohoku region. 24 municipalities are responsible for the water quality conservation, which can be achieved by identifying the cause of stream degradation and coordinated source control. To project the future stream water quality, this study attempts to analyze the long-term change and current status in relation to the watershed development and quality management based on historical data and field measurement.

2. STUDY AREA

The Abukuma Watershed (Figure 1) has an area of 5,600km^2 and the population of 1.5 million. The population is dense along the west side of the mainstream. 69 sub-basins join the mainstream. Coniferous and broadleaf forests, the dominant land use in uplands, cover 60% of the entire watershed. Paddy field and cropland are the significant land use in areas between the upland forest and the mainstream, each comprising 15% of the watershed. Two dams and a weir are located in the mainstream reaches H-I and C-D, respectively, for the hydropower generation. Many dams are located in sub-basins for agriculture, drinking water and flood control. A biggest one has the net storage volume of 148 million m^3. Five wastewater treatment plants (hereafter WWTPs) directly discharge into the mainstream at W1 ~ W5 (Figure 1).

3. LONG-TERM WATER QUALITY CHANGE

The long-term trend of stream water quality can be captured by the monthly data monitored at multiple stations for the period of 1961–2005. Figure 2 shows monthly water quality histories and running averages over 6 months at stations E, F, I and K

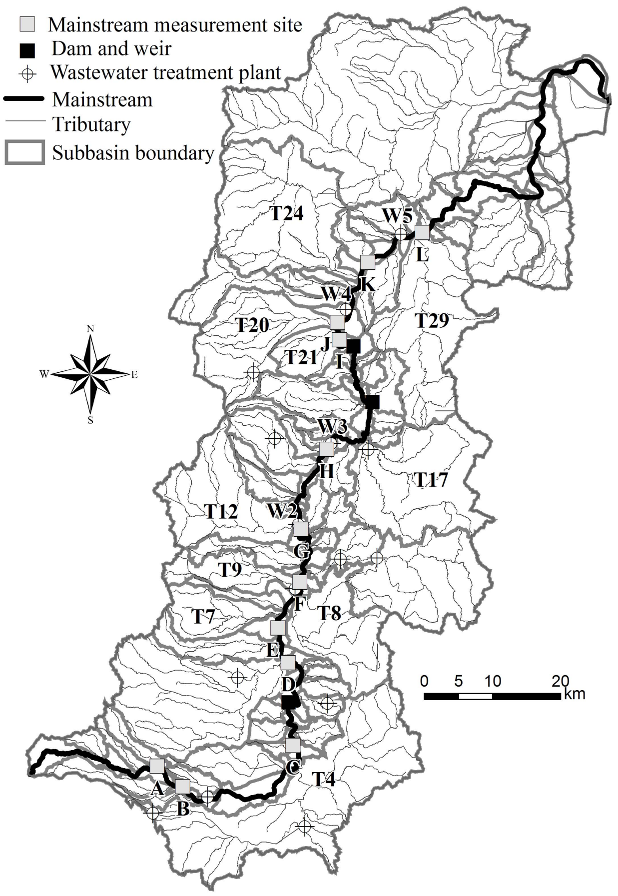

Figure 1. Abukuma River Watershed with the mainstream, sub-basins and tributaries.

(Figure 1). It is found that the long-term change of BOD can be divided into three stages depending on the periods. The water quality level in 1960's and 70's was quite poor, which can be attributed to the economic growth accompanied with urban development and industrialization. During these periods, heavily polluted wastewater from domestic and industrial sectors was discharged into streams without proper regulations and treatments. From around 1975 until the end of 90's, BOD has been greatly reduced on annual average but still exhibited higher values during irrigation seasons. This improvement is explained by the enforcement of water quality related laws and standards during 1967~1970. Under the law, the Environmental Quality Standards (EQS) were set for the stream water BOD and other indices such as DO and SS. The quality of wastewater discharged into stream from specific facilities was also regulated by the water pollution control law. On the other hand, non-point sources of nutrient from farmlands and livestock have not been subjected to the regulation, and thus becoming the major cause of water quality degradation during this period. It can be seen that BOD concentration and its seasonal variation were reduced since late 1990's. This could be explained by the improvement of the sewerage system and dissemination of septic tanks. The percentage of people provided with the sewerage system was increased from 27% in 1989 to 40% in 2003. However, it seems that the change in the mainstream water quality is not sensitive to the improved quality of wastewater from the domestic sector during the past few decades (Figure 3). It must be noted that the annual rainfall and streamflow has a slightly increasing trend over the watershed for the same period, which denies the possibility of decreasing natural freshwater components.

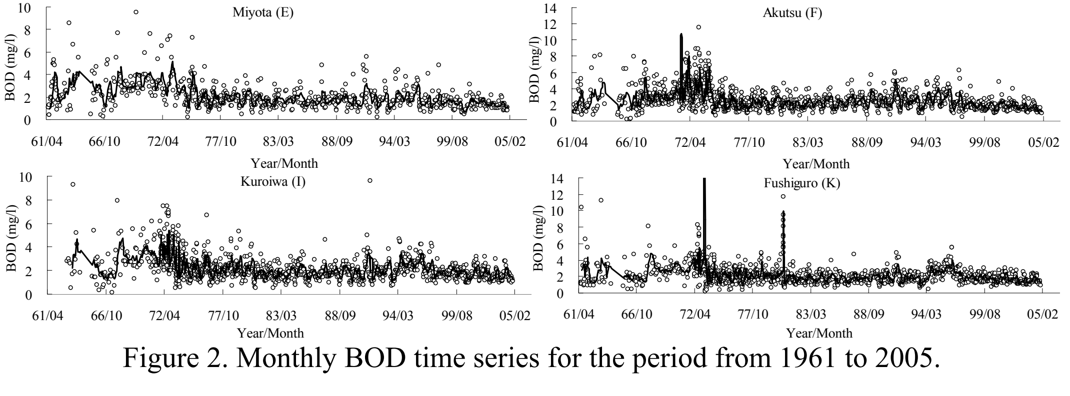

Figure 2. Monthly BOD time series for the period from 1961 to 2005.

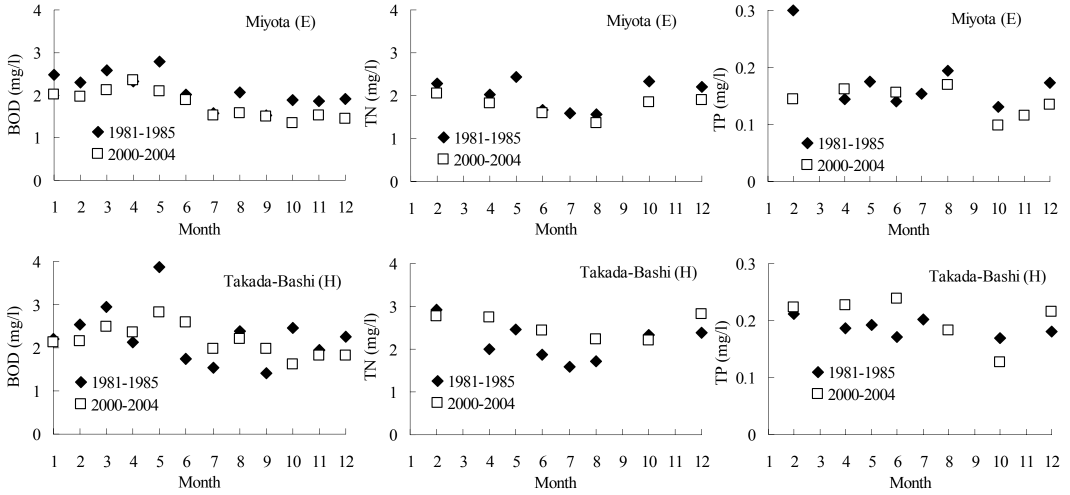

Figure 3. Mean monthly BOD, TN and TP for 1981-1985 and 2000-2004.

4. WATER QUALITY AT PRESENT

4.1 Field measurement

The main sources and their locations causing mainstream pollution have not yet been clarified, although it is quite significant for appropriate and efficient water quality management. We conducted an intensive measurement in March 2006 to reveal the source, transport and fate of pollutants in a non-irrigated season, when the hydrological effect of irrigation is negligible. We collaborated with authorities in charge of the routine water quality measurement, i.e., the local office of MLIT, Fukushima Prefecture, Fukushima City and Kooriyama City. This measurement covered 57 stream locations (12 in the mainstream and 35 in the tributaries) and effluents from 2 WWTPs (W2 and W3). Streamflow was measured on site or converted by the relationship between water level and flow rate. Water was sampled for the chemical analysis of BOD, DO, pH, SS, total nitrogen (TN), total phosphorus (TP), NO_3-N, NO_2-N, NH_4-N, PO_4-P, Cl^-, chlorophyll-a and stable isotope ratio of nitrogen ($\delta^{15}N$).

4.2 Characteristics of stream water quality

The measured concentration of tributaries and WWTPs is presented for BOD, TN and TP in Figure 4. BOD ranges from less than 0.5 up to more than 20 mg/l. TN is higher at the most downstream location in each sub-basin. TP at a few sites is extraordinary high, and strongly affects mainstream TP concentrations.

In order to detect the sources of pollutant in tributaries (point or non-point, human or natural, urban or agriculture), the relation between land use and pollutant concentration and load was investigated for BOD, TN, NO_3-N, NH_4-N, particulate N, TP, PO_4-P and particulate P. Except for two plots of high BOD level, the concentration and load of BOD are moderately related to the percentage of built area in a sub-basin (Figure 5), which suggest dominance of both point and non-point sources. The inverse relationship between the BOD concentration and the percentage of forested area is more correlated. NO_3-N is strongly related to the percentage of cropland, except for one site (open circle) possibly influenced by the upstream point source (manufacturing factories). NO_3-N load per unit basin area (NO_3-N × Discharge /Area) showed little correlation to the percentage of cropland because the flow discharge depends on the area and the presence or absence of the reservoir operation and snowmelt. Similarly, NH_4-N and particulate N were related to the percentage of built area and forested area with some exception, respectively. Phosphorus was mostly influenced by a variety of human impacts, i.e., wastewater from manufacturing industry and fish-raising industry, sediment runoff due to construction works, and low-quality effluents from septic tanks and treatment plants. A relationship between TP and the percentage of built area (Figure 5) was selected to give moderate estimate of TP loadings. In the subsequent study of mass balance in the mainstream, those relationships were applied to calculate loads of BOD and nutrients from sub-basins where we have no measurement data.

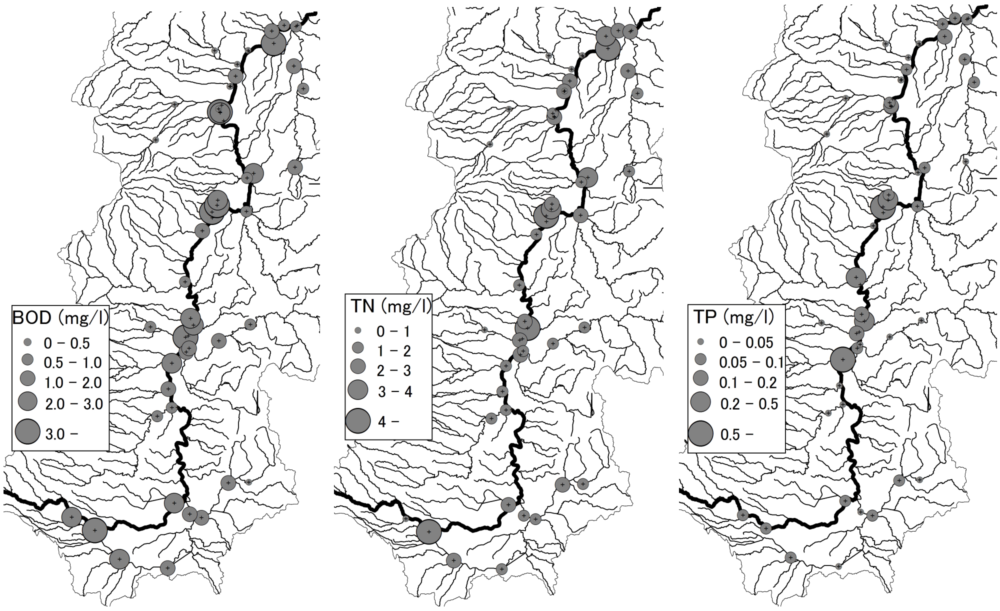

Figure 4. BOD, TN and TP concentration of tributaries and WWTPs effluents.

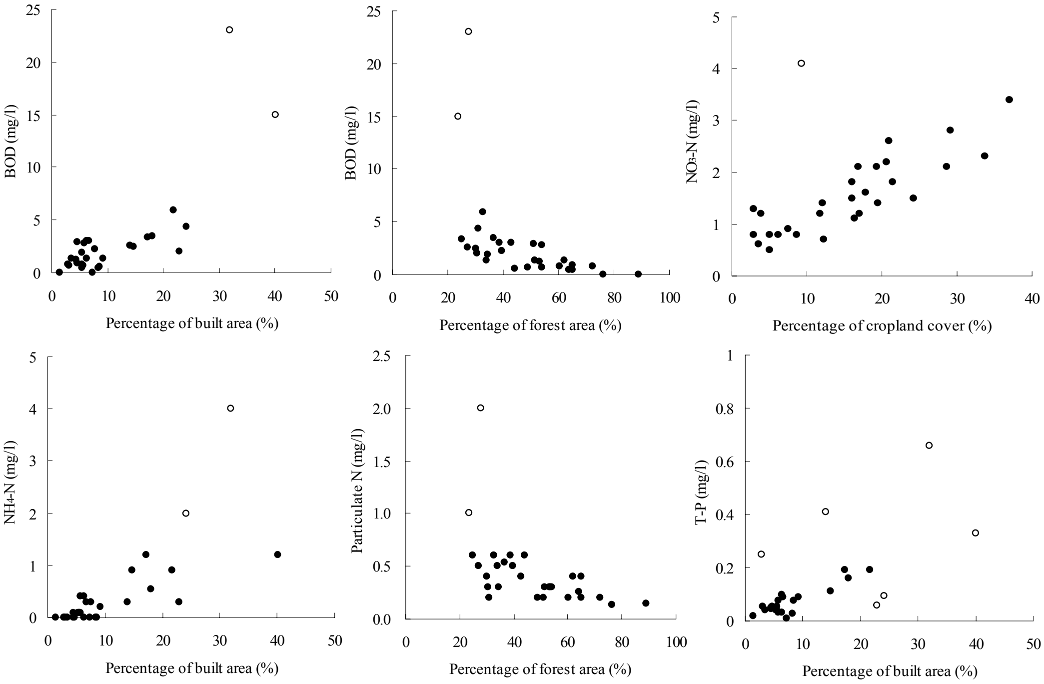

Figure 5. Relationship between land use and concentration of BOD and nutrients. Open circle was excluded when derive a regression curve that was used for further analysis.

4.3 Water quality change along mainstream

The longitudinal variations of BOD, TN and TP are due to the load inflowing from tributaries, WWTPs (wastewater treatment plants) along the mainstream, and chemical, biological and physical processes in the stream. If the flux of BOD, TN and TP decreases as water flows down between 2 adjacent locations, it is an evidence of net removal of pollutants by those processes.

Figure 6 shows streamflow, concentration and flux of BOD, nitrogen and phosphorus at 12 mainstream locations. Locations of wastewater discharge and main tributaries are referred to Figure 1 and 7. Different behaviors are found for the concentration of BOD, nitrogen and phosphorus along the mainstream. BOD increases considerably in reaches between B-C and F-G-H. The former is owing to the inflow from agricultural tributaries, while the latter is due to the inflowing loads from urbanized streams and WWTPs. Both BOD concentration and flux decrease in reaches C-D and H-I, which is attributed to the settlement of particulate components while flowing through a stagnated zone near the mainstream dams and weir. Similar to BOD, TN and NO_3-N concentrations significantly increase in reaches B-C and F-G-H. However, the flux through the dams and weir does not decrease, probably due to the high ratio of dissolved inorganic components. It is clearly seen that NH_4-N turns into NO_3-N by nitrification in the reach H-I.

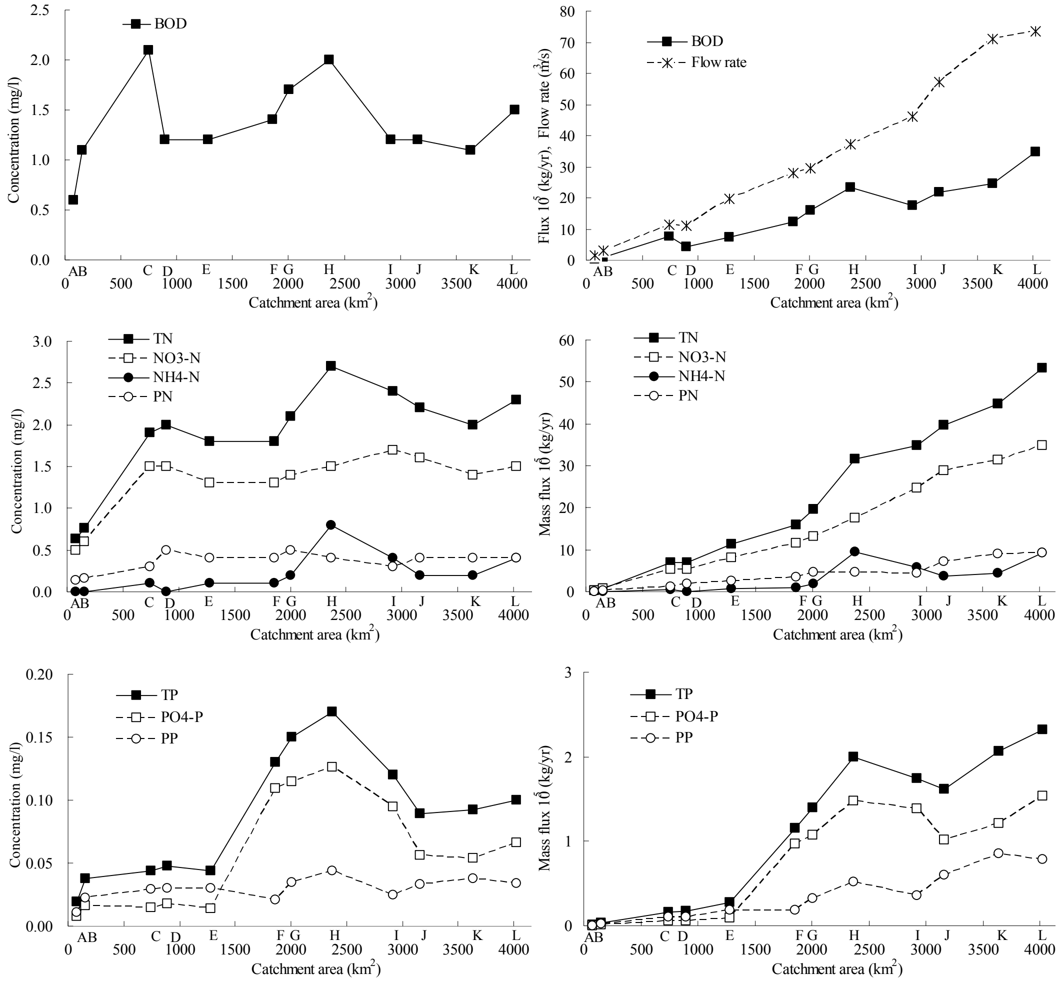

Figure 6. Streamflow and water quality at 12 mainstream locations.

TP and PO_4-P significantly increase between E and F, where a huge amount of phosphorous is brought into the mainstream from one tributary, which collects wastewater from fish-raising ponds. PO_4-P flux, a dissolved component, decreases in reaches H-I and I-J, which are not likely due to the settlement of particulates. The uptake of PO_4-P by the growth of phytoplankton is a possible reason for the reduction in the reach H-I. The reduction in PO_4-P flux between I and J can be attributed to the adsorption to soil particles and/or flocculation with cations like Fe^{3+} and Al^{3+}, as the particulate phosphorous increases in this reach. A tributary runs into the mainstream with relatively high acidity is the possible source of soil particles and/or cations.

4.4 Mass balance in mainstream

As was seen in previous sections, water quality in the Abukuma Watershed is strongly dependent on various human impacts, i.e., the wastewater from domestic, industrial and stock farming sectors, and non-point pollutant loads from agricultural lands. Improvement of the sewerage system and dissemination of septic tanks has been carried out to reduce pollutant loads from point-sources, but only a small effect is found. It has not yet clarified how much impact is posed by the stock farming. It should be investigated how much and where major pollutant loads are generated and flow into mainstream through tributaries. It is also significant to quantify mass balance of pollutants and estimate the self-purification function in the river system.

Figure 7 presents measured and estimated pollutant loads to the mainstream from the downstream end of each tributary and WWTP, in which A~L indicate mainstream measurement locations, T1~T29 tributaries, W1~W5 wastewater treatment plants, U1~U11 un-gauged tributaries. Pollutant loads from un-gauged tributaries are calculated from the previously described relationships between BOD, TN (NO_3-N, NH_4-N, particulate N), TP concentrations and land use, giving a constant streamflow per unit area of sub-basin ($=0.0112 m^3/s/km^2$).

As an overall characteristic, BOD, TN and TP loads inflowing from the left hand side of the mainstream tend to be large. BOD loads from T9 and T21 are larger than any other tributaries. Those tributaries shed from areas that are densely inhabited and less provided with sewerage system. BOD loads from T4, T8 and T29 are large, because those watersheds are large and collect pollutants from a variety of non-point and point sources and hold large dams upstream (T4 and T8). Tributaries T4, T8, T17, T20, T24 and T29 are major TN input to the mainstream. Croplands in watersheds T4, T8, T17 and T29 are larger than any other watersheds, which implies that the fertilizer is the main source of TN. Watersheds of T20 and T24 have lower percentage of farmland, and famous for the immaculate water upstream. However, they are also popular for hot springs and thus human impacts are inevitable. The impact of TN from wastewater effluent W2 is larger than any single tributary, which is due to poorly treated effluents. Tributaries with large TP load (T7 and T12) are neither classified as major sources of BOD nor TN. It is supposed that the sources of TP in T7 and T12 are the wastewater from the fish-raising industries and the manufacturing industries, respectively.

Changes in streamflow and BOD, TN, TP flux between sites B and K are presented in Figure 8. In each graph, upper bar indicates flow or flux at site B plus input from tributaries and WWTPs. Flow 1 and load 1 are the sum of the measured discharge and load, respectively, inflowing from tributaries and WWTPs between B and K. Flow 2 and load 2 are the sum of the estimated discharge and load, respectively, inflowing from un-gauged tributaries. Flow rate and TN are almost the same between upper and lower bars, which suggests the conserved flow and TN between sites B and K. BOD and TP show large discrepancies between upper and lower bars. These discrepancies indicate the existence of some processes that reduces BOD and TP load in the mainstream. Figure 9 shows flow and flux changes within a reach between sites F and H, where a great amount of loads is missing. This figure suggests the existence of unidentified flow and loads of BOD, TN and TP. This is partly explained by the underestimates of discharge and loads from un-gauged tributaries between F and H. This underestimate may be caused by streams highly contaminated with nutrients from point and non-point sources such like stock farming sectors or contaminated ground water seepage. Thus, it is clear that those undetected loads must be taken into account in order to quantify the removal of nutrients by chemical, biological and physical processes.

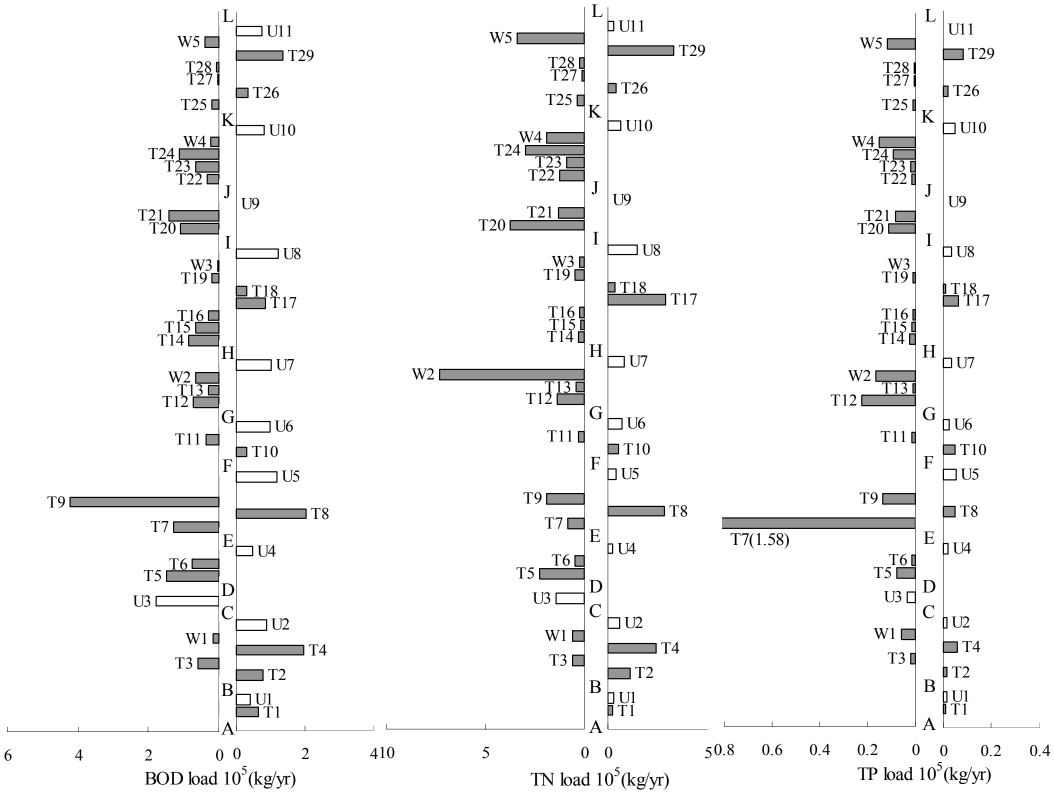

Figure 7. BOD, TN and TP loads inflowing to mainstream. A ~ L: mainstream measurement locations (A is the most upstream location), T1 ~ T29: tributaries, W1 ~ W5: WWTPs, U1 ~ U11: Ungauged tributaries. Each bar indicates the magnitude and location of pollutant load input to the mainstream from tributaries or wastewater treatment plants.

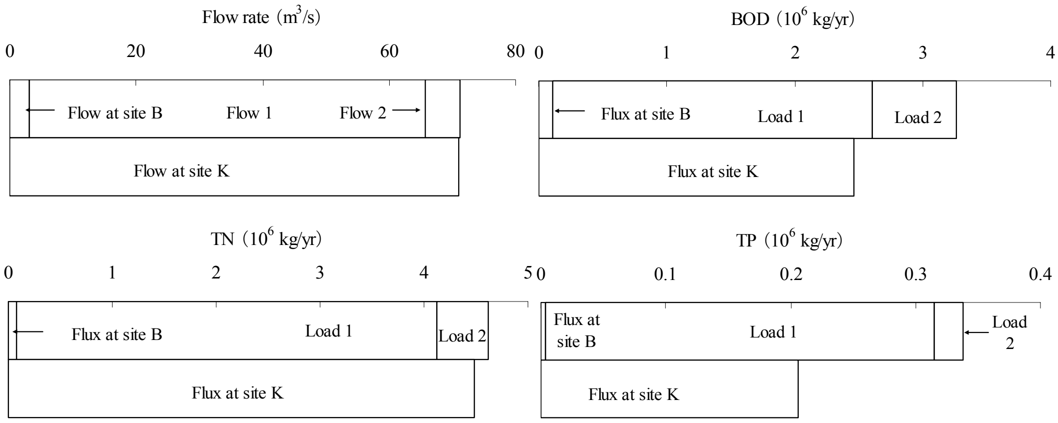

Figure 8. Flow rate and BOD, TN, TP flux changes between sites B and K.

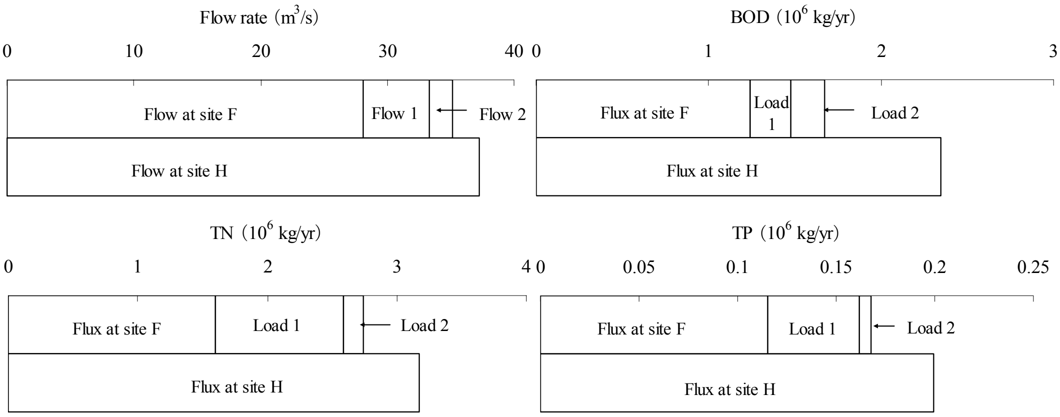

Figure 9. Flow rate and BOD, TN, TP flux changes between sites F and H.

5. CONCLUSION

This study investigated long-term stream water quality change and present status in the Abukuma River Watershed. The nutrient concentration for two periods separated by 15 years showed a little change or even worsened in some months at mainstream locations, despite the improvement of wastewater treatment facilities. Water quality in tributaries showed strong correspondence to the land use. NO_3-N is particularly related to the percentage of cropland, and BOD, NH_4-N and TP to the percentage of built area in each sub-basin. BOD and nutrient in the mainstream is likely affected by chemical, biological and physical processes in the flow such as deposition, adsorption and flocculation, in addition to the inflow from specific tributaries.