The effect of small impoundments on nutrient transport in a suburban watershed

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Abstract The objective of this study was to confirm the effect of small impoundments on nutrient transport on a catchment scale. We examined the effect using the ratio that dissolved nitrogen (DN) is divided by Cl^-. The ratio increased in the summer season and decreased in the winter season at the outlet of the impoundments. The reason for decreasing of the ratio may be explained by the decline of DN concentration, by assimilation or denitrification. The relation between residence time and magnitude of nitrate removal showed that long residence time can lead to greater reduction of nitrate. However, DN was produced in larger impoundments and sediment interaction may occur as a result. Therefore, smaller impoundments may be more effective for nitrate attenuation than larger ones. From the results, small impoundments management is important for better water environments in a watershed in future, because it has a potential for nutrient removal that can be used more positively for improving water quality at a local scale.

Key words small impoundment; residence time; nitrogen removal

INTRODUCTION

Residence time of lakes and reservoirs is an important factor for nutrient transportation because it controls biological reactions such as assimilation by phytoplankton and denitrification that strongly affect nutrient retention. As a result of these processes, a number of reservoirs have suffered from eutrophication. In particular, small impoundments may influence the local water environment on a watershed scale because very large numbers ($>10^8$) of small impoundments are distributed in the world (Wetzel, 1990). Therefore, it is important to consider the effect of nutrient retention of the small impoundments for watershed management. Previous studies show that small impoundments can affect nutrient transport in a catchment due to nutrient retention like large reservoirs (Prochnow *et al.*, 2007; Shimizu *et al.*, 2009, 2011, etc.). Shimizu *et al.* (2009) confirmed the relationship between reservoir size and amount of dissolved nitrogen removal. However, there is little known about the effect of small impoundments on nutrient transportation at a catchment scale. In particular, limited studies confirmed the relationship with residence time. Therefore, the objective of this study is to confirm the effect of small impoundments on nutrient transport on a catchment scale.

STUDY AREA AND METHOD

The study area is located on the upper region of Yamato River watershed (1070 km^2) located between Osaka and Nara prefectures in Japan (Fig. 1). The study area is characterized by temperate climate, with mean annual precipitation of 1270 mm and mean temperature of 15.1ºC. There are large numbers of small impoundments on the mainstream for irrigation into rice paddy fields. This river is also known as one of the most contaminated rivers in Japan, due to domestic wastewater because of rapid urbanization and intensive development of industry after the late 1950s. Although the situation has been recovering due to spread of sewage treatment systems, it has still been influenced by the domestic wastewater.

Monthly observed concentrations of dissolved nitrogen (DN; NO_3^--N, NO_2^--N, NH_4^+-N) and chloride (Cl^-) at the Nukatabetaka Bridge monitoring station were obtained from the MLIT Water Information System (http://www1.river.go.jp/) for seasonal variation. Water samplings of the inlet and outlet of 10 small impoundments with one sewage effluent were conducted two times; summer season (August 2012) and winter season (January 2013) (Table 1). According to Willis *et al.* (2002), small impoundments are defined as waters <40 ha (400 000m^2) in surface area. Hence, these sampling sites can be considered as small impoundments from the definition because the surface areas of all sites are <400 000 m^2. Water samples were collected into polypropylene test tubes after filtering with 0.2 µm cellulose ester membrane filters. These samples were analysed for concentrations of DN by colorimetric methods (swAAt, BL-tec) and for chloride (Cl^-) by ion chromatography (HIC-SP, Shimadzu). Measuring of the water depth of the impoundments was conducted at the same time as water sampling.

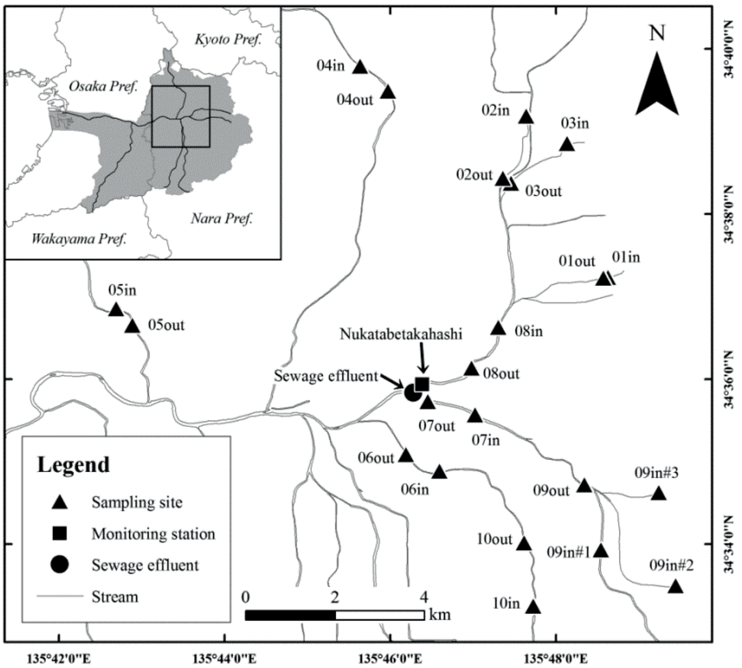

Fig. 1 The study area.

Table 1 Characteristic of the impoundments.

Sampling site	Storage capacity (m^3) Sep.	Jan.	Depth (m) Sep.	Jan.	Surface area (m^2) Sep.	Jan.	Residence time (days) Sep.	Jan.
01	884	105	1.7	0.2	520	525	9.67	0.01
02	17160	3088	3.0	0.4	5720	7720	10.48	1.89
03	51000	3000	3.4	0.2	15000	15000	0.74	0.04
04	52620	52600	3.0	3.0	17540	17540	2.03	3.04
05	21630	2524	3.0	0.4	7210	6310	0.12	0.05
06	12960	2590	1.0	0.2	12960	12950	0.19	0.07
07	62832	83524	3.4	3.4	18480	24566	6.06	3.22
08	118350	120546	3.0	3.0	39450	40182	2.04	0.93
09	156870	236190	3.0	3.0	52290	78730	4.54	6.83
10	68530	68536	2.2	2.2	31150	31153	3.97	2.64

RESULTS AND DICUSSION

Seasonal variation of DN:Cl^- ratio

Figure 2 shows the variation of DN:Cl^- ratio observed at the Nukatabetakahashi from 2006 to 2010. The upper stream within 1 km from the monitoring station was in almost a lentic condition due to a cascade of 13 weirs behind the monitoring station. The seasonal variation indicates that the ratio decreased in the summer season and increased in the winter season. Although the mean ratio of DN:Cl^- in winter was 0.07, that is close to local domestic wastewater, the ratio in summer season was below 0.07. The ratio cannot be varied seasonally if most of the DN and Cl^- were supplied from the domestic wastewater that is constantly inflowing throughout the year. Theoretically, decline of DN concentration or inflowing of the water with concentrations of low DN and high Cl^- can decrease the ratio. However, there was no chance for mixing with treated water (low DN and high Cl^-) because no sewage treatment plant is located in the catchment of the monitoring station. Furthermore, previous studies show that seasonal variation of nutrient can be confirmed when the residence time was over a specific threshold because phytoplankton affect the water quality. Thus, it can be explained that the ratio decreased in the summer season due to a decline of DN concentration by biological reactions, such as assimilation or denitrification, while there was little change from domestic wastewater due to fewer activities of biological reactions in winter season. Therefore, small impoundments could affect attenuation of DN, especially in the summer season.

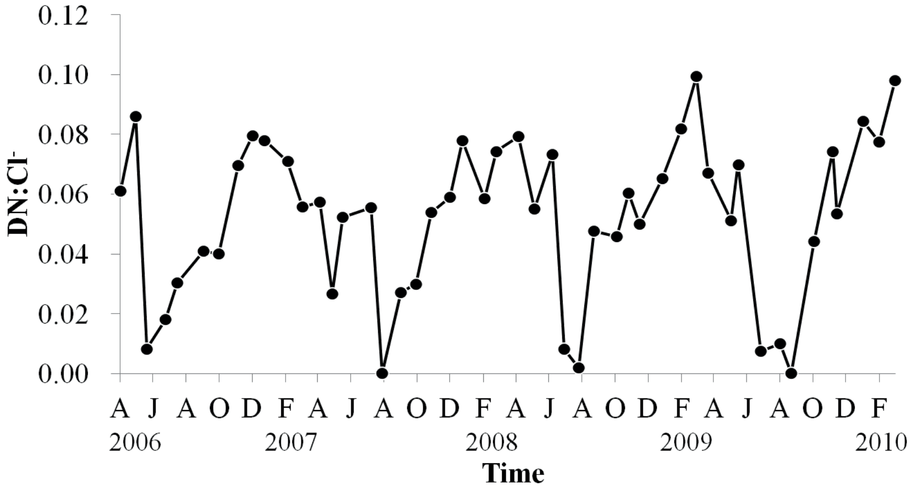

Fig. 2 Seasonal variation of the DN:Cl^- ratio at Nukatabetakahashi monitoring station.

Difference of DN:Cl^- ratio between inflow and outflow

Figure 3 shows that variation of DN:Cl^- ratio at inlet and outlet of the impoundments. The mean ratio of winter season was greater than the summer season. This result was basically the same as the seasonal trend that was confirmed from monitoring records in the last section. Furthermore, variations of the ratio after the impoundments in September were greater than in January. There are two possibilities to explain the results. First, the magnitude of difference of the ratio between seasons could be caused by a difference of water temperature that controls biological reactions, because the mean water temperature in September was 27.8ºC while that in January was 7.1ºC. Secondly, the water storage capacity of some of impoundments was changed in January due to unnecessary irrigation. The magnitude of difference of the ratio between impoundments could be influenced by water storage capacity changes because it can lead to changes in the residence time. From these results, the ratio may be affected by water temperature and residence time.

Relationship between residence time and removal of dissolved nitrogen

Figure 4 shows the relationship between residence time and difference of concentration of nitrate (a) and dissolved nitrogen (b). The decrease of nitrate was strongly negatively correlated ($r = –0.60$) with residence time (Fig. 4(a)). This result indicates that a greater decrease of nitrate

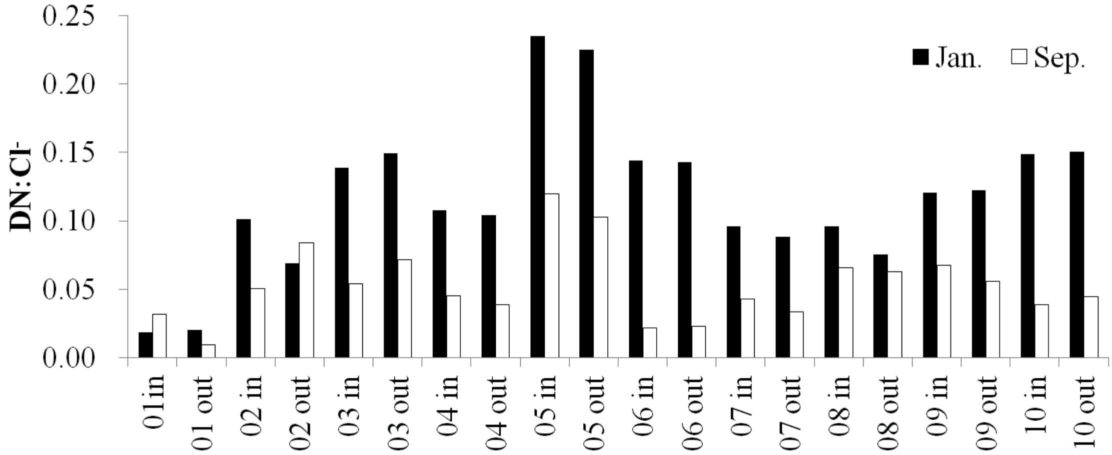

Fig. 3 Variation of DN:Cl^- ratio at inlet and outlet of the impoundments.

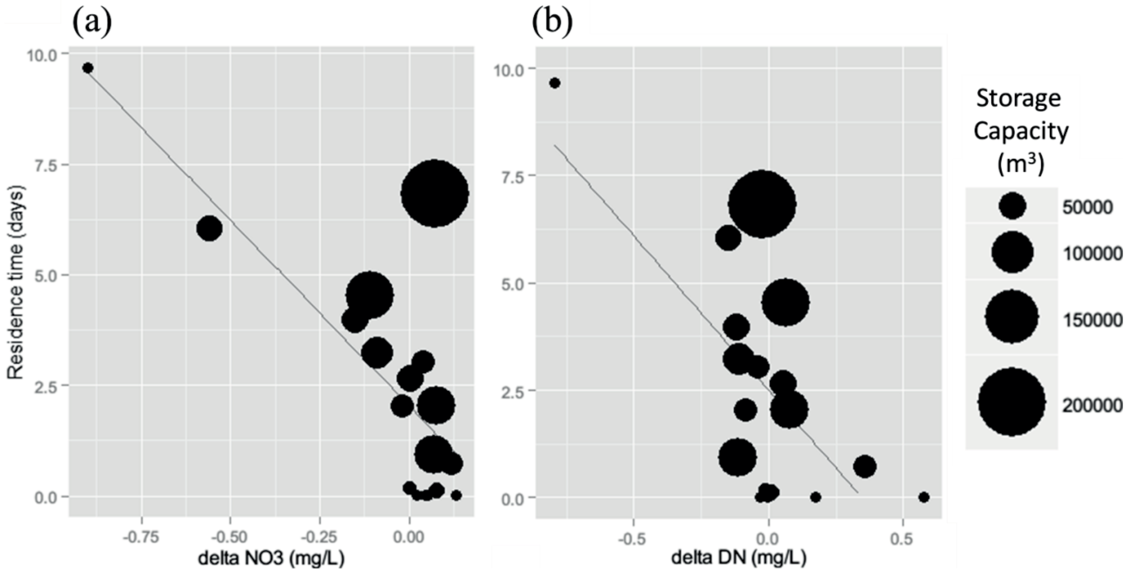

Fig. 4 Relationship between residence time and difference of NO_3 (a) and DN (b) concentration.

confirmed when it was a relatively long residence time. The attenuation of nitrate could be caused by phytoplankton growth in this study because the correlation between Δ saturated DO and Δ pH (r = 0.83) was confirmed from observed data (not shown). In addition, one of the main reasons for nitrate removal in the study watershed was assimilation by phytoplankton, according to Taniguchi *et al.* (2004). The intercept of the linear regression of the relation is 2.04; that means nitrate attenuation would occur when the residence time is greater than 2 days.

Generally, reservoirs that have a high nutrient concentration and long residence time can change their water quality with increase of phytoplankton growth. However, biomass of phytoplankton in reservoirs can be decreased by less than 1 week of residence time because phytoplankton cannot be held in the water body due to an increase of water exchange rate (Uhlmann, 1968). Hence, phytoplankton could bloom with a long residence time, which is greater than 8–14 days in typical reservoirs (Olding *et al.*, 2000). However, approximately 2 days is less than the residence times that were reported in previous studies. The doubling time of phytoplankton at optimal depth of photosynthesis was reported to be 0.12–7.5 days (Westlake, 1980). Releasing of phytoplankton from reservoirs located upstream can increase the amount of phytoplankton and its production rate in reservoirs located downstream (Petts, 1984). In particular, water released from the surface layer is more effective because the phytoplankton is alive although what is in the bottom water is dead (Stroud & Martin, 1973). These small impoundments can release stored water downstream only by overflow, which means the surface water can always be discharged. In addition, the small impoundments are connected in sequence from upstream to downstream like a cascade connection, because a small impoundment can cover a small irrigation area. Hence, it is suggested that small impoundments are more effective for nitrate attenuation than large ones.

However, the attenuation of nitrate had a clear relationship with residence time of dissolved nitrogen (Fig. 4(b)). It is suggested that mineralization of organic matter that was accumulated in the sediment can supply dissolved nitrogen to the water bodies. Generally, there is a high concentration of ammonia in sediment pore water which is regenerated by organic decomposition. Shimizu *et al.* (2011) confirmed that an interaction between the water column and sediment pore water could bring ammonia of pore water into its water body by diffusion in small impoundments that are of the same scale as in this study. The result shows that the impoundments with large capacity might have relatively large regeneration (Fig. 4(b)). There is a possibility that the large impoundment could be changed from sink to source in terms of the net nitrogen budget. However, the small impoundments would be a better condition for nitrate attenuation due to lentic conditions and shallow depth.

CONCLUSION

The objective of this study was to confirm the effect of small impoundments on nutrient transport on a catchment scale. We examined efficiency of small impoundments for dissolved nitrogen removal in the water bodies using the DN:Cl^- ratio as an indicator. Seasonal variations of DN:Cl^- ratio at a downstream of impoundments was confirmed from the observed record. The result indicated the mean ratio is decreased in the summer season while it is almost the same as for domestic wastewater in the winter season. Furthermore, the magnitude of difference of the ratio between inlet and outlet of the impoundments in the summer season was greater than the winter season. From these results, the reason for the decrease of the ratio may be explained by the decline of DN concentration by assimilation or denitrification, especially in the summer season. The relation between residence time and magnitude of nitrate removal showed that long residence time can lead to greater reduction of nitrate. The threshold residence time of starting attenuation for nitrate was estimated to be 2 days, i.e. shorter than large impoundments of 8–10 days. However, the relations of DN implied that large impoundments can be changed from sink to source by interaction with sediment. Therefore, it was suggested that smaller impoundments may be more effective for nitrate attenuation than larger impoundments.

Consequently, it was confirmed that small impoundments can take an important role in nutrient transportation. The nutrient removal effect of small impoundments has been confirmed worldwide (Cooper & Knight, 1990; Ejsmontkarabin *et al*., 1993; Jeppesen *et al*., 2007; Prochnow *et al*., 2007; Shimizu *et al*., 2009). It has a potential for nutrient removal that can be used more positively for improving water quality at a local scale. Nevertheless, limited studies about management of small impoundment were done previously. Thus it is important to consider reservoir management of small impoundments for a better water environment in a watershed as a future prospect.

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