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# Effect of frequent storms on nutrient discharge in a mountainous coastal catchment, western Japan

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**Abstract** In order to forecast the variation of nutrient load with climate change, the long-term change in rainfall and its effect on river runoff in a study catchment were investigated and related to change in nutrient discharge to the ocean. In the study area there has been a decreasing rainfall trend for 40 years but the frequency of large rainfall events has remained constant. The annual runoff decreased by 60 mm in the last 40 years, but large annual runoff amounts were observed in years with large rainfall events. The nutrient discharge also reflected the rainfall and runoff trends. DN load has increased in the long term, while in drought years DP load has increased, reflecting the dominant groundwater contribution with significantly higher DP concentrations in such conditions.

**Key words** groundwater; heavy storm event; nutrient discharge; river

## INTRODUCTION

In estuaries, inland seas and coastal areas, the occurrence of eutrophication and anoxic conditions represent critical environmental problems (Burt *et al.*, 1993). To conserve the coastal environment for the 21st century, it is important to estimate and manage the variation in nutrient discharge from coastal catchments, especially due to the effects of climate change. Both storm frequency and rainfall intensity have been increasing over the last 20 years in temperate and humid regions (McCathy *et al.*, 2001). However, both the number and intensity of drought periods has also been increasing. Such climate changes may influence nutrient, as well as water, discharge in watersheds. It is likely that this effect would be larger in the Japanese river catchments than in many other regions, because of the mountainous headwaters and relatively high river bed gradients.

In addition, recent research has shown that not only rivers, but also groundwater exerts a strong influence on nutrient discharge from land to the sea (e.g. Zektser & Loaiciga, 1993; Slomp & Cappellen, 2004). Groundwater discharge is particularly significant in Japanese catchments draining deltaic areas, because of high aquifer permeability related to coarse grained sediment, and due to high gradients. To forecast future nutrient discharge in such steep catchments, it is necessary to investigate how nutrient discharge varies with both river flow and groundwater in the different climatic conditions of storm and drought.

The present study investigates the variation in nutrient discharge associated with river flow and groundwater using long-term records of water quality and runoff, and seeks, in particular, to evaluate the effect of frequent storms. This research focuses on the nutrients of dissolved nitrogen (DN), dissolved phosphorous (DP) and dissolved silicon (DSi).

## STUDY AREA

The study area is the River Ashida catchment in the Hiroshima Prefecture of western Japan (Fig. 1). The main river flows from the Chugoku Mountains into the Seto Inland Sea and has a length of 86 km and a catchment area of 860 $km^2$. Maximum altitude in this catchment is about 700 m, and this summit is in a middle stream area. The landscape is generally hilly in the upstream area, mountainous in the middle part of the catchment, and a mixed hilly and flat terrain in the downstream area. The catchment is mainly underlain by granite, and 10% of the area is covered by alluvial sediment with a thickness of more than 10 m, which is located mainly on the flat lowland around the river from the middle reaches downstream. There is a small delta at the river mouth, where the alluvial sediment reaches a maximum thickness 40 m with an average value of 20 m (Fig. 1). The average annual rainfall is about 1100 mm, which is two-thirds of the average amount for the whole of Japan. Monthly rainfall is highest in the rainy season during June and July.

Approx. 90% of the catchment is characterized by sloping ground and it is mainly covered by forest, with agricultural and residential areas comprising approx. 10 and 2%, of the catchment, respectively. A population of 700 000 lives in the catchment and is mainly concentrated in Fukuyama City (500 000). Sewage systems are in place for approx. 70% of the urban area in Fukuyama City, but for less than 40% of the sub-urban area. Levels of river contamination are among the most serious in western Japan, and downstream BOD concentration is more than twice the environmental standard value. Consequently, although the Seto Inland Sea is designated as a Japanese National Park, eutrophication and the occurrence of red tides have been unsolved environmental problems.

## DATA

Daily river runoff and rainfall data at a downstream location have been collected for more than 30 years by the Japan Land, Infrastructure and Transportation Ministry and the Japan Meteorological Agency. Hourly runoff data are also available since 1988. In addition, dissolved chemical parameters, including the nutrients DN, DP, and DSi, have been monitored monthly in the River Ashida in the Seto Inland Sea region.

The level and quality of groundwater have been investigated by the Fukuyama City Office for more than the last 10 years. However, in order to provide further information on temporal and spatial variation in groundwater quantity and quality, water level was recorded and samples were collected in the present study at 22 dug wells and four boreholes in July 2006. pH, EC (electrical conductivity), and ORP(oxidation–reduction

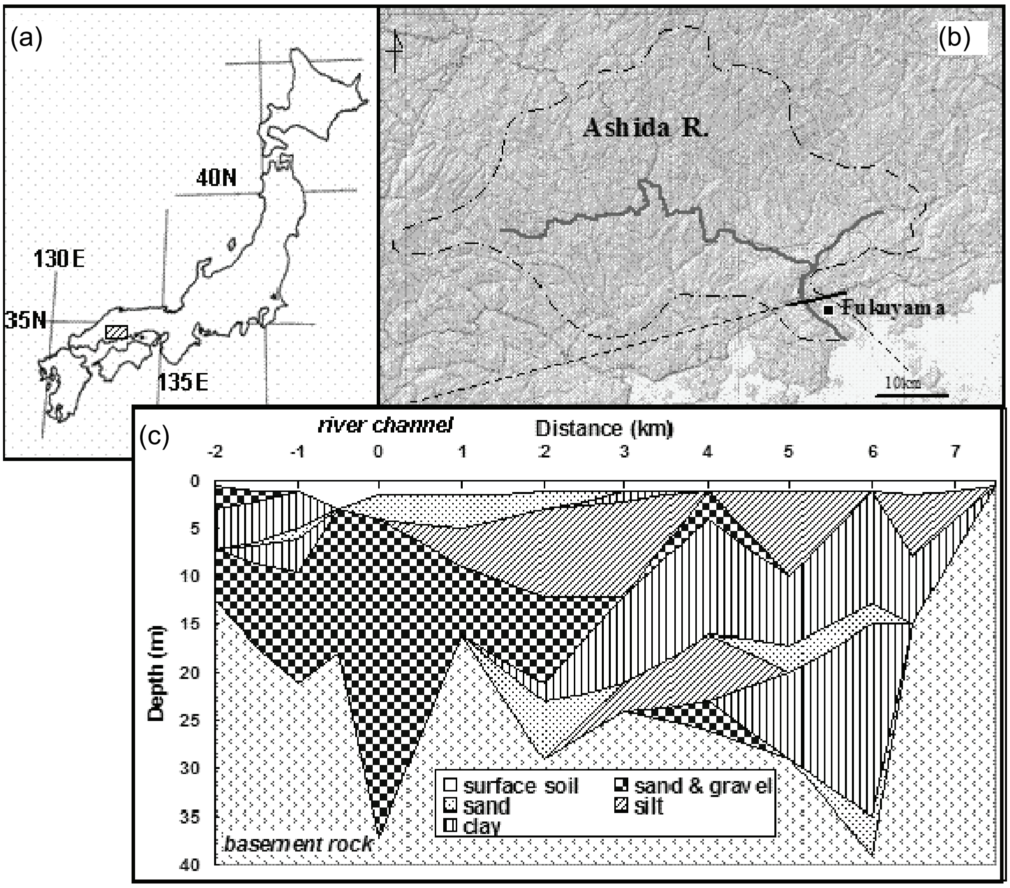


**Fig. 1** Location of study area and geological profile of the river delta.

potential) were also measured at the time of water sample collection. Data collected by the Fukuyama City Office, suggested that variation in water levels between adjacent wells was less than 1 m. Nitrate ($NO_3^-$) and chloride ($Cl^-$) concentrations were analysed in the laboratory by ion chromatography after filtering using a 0.20 µm cellulose ester filter. In addition, DN, DP and DSi were analysed by spectrophotometer. Dissolved organic carbon (DOC) was analysed using a TOC analyser.

## RESULTS AND DISCUSSION

### Long-term change in rainfall properties and their effect on river runoff

Figure 2 shows the variation and trend in annual rainfall and frequency of large rainfall events (>100 mm) over the last 46 years. Annual rainfall shows a decreasing trend with a decrease of 40 mm per decade and suggests the progress of drought. However, the frequency of large rainfall events is approximately constant in the study period so that relative to the annual rainfall they appear to be becoming more important. For example, five large events occurred in 2004, a number only exceeded in 1972, while the annual rainfall of 1400 mm recorded in 2004 ranked only the seventh highest in the study period.

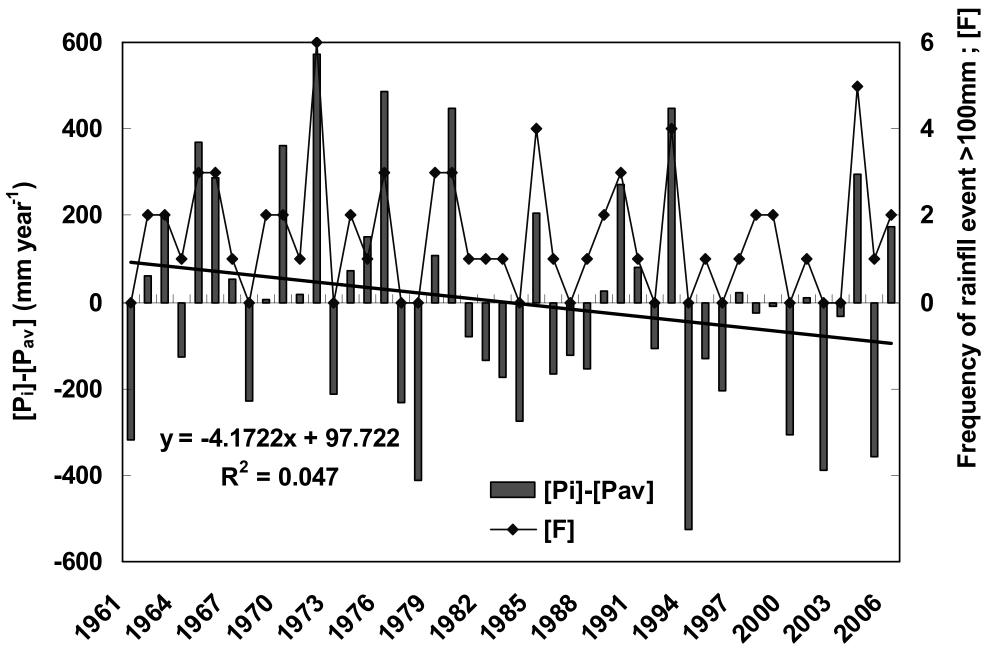


**Fig. 2** Variation and its trend of annual rainfall and number of large rainfall events (>100 mm) in the study period.

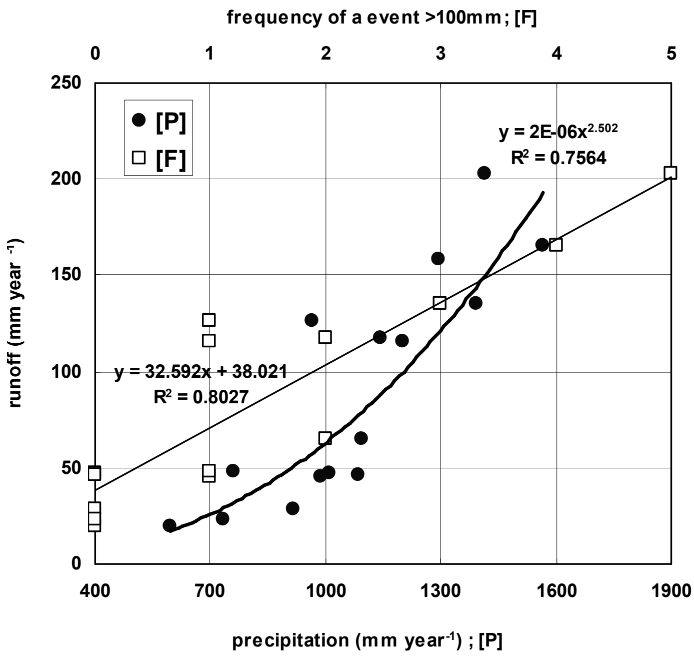


**Fig. 3** Relationships river runoff and annual rainfall amount and frequency of large rainfall events in the period 1988–2003.

Figure 3 shows the relationship between both the annual rainfall and the frequency of large rainfall events per year, and annual river runoff for a 15-year period since 1988. River runoff not only increases with increasing rainfall amount, but also with the frequency of large rainfall events. Figure 3 suggests annual river runoff has decreased by 60 mm over the last 40 years in response to a decrease in annual rainfall of approx.

160 mm. However, the increase in runoff with one large rainfall event is estimated to be 32 mm. Therefore, it is suggested that even if the annual rainfall decreases in the long term, the river runoff would increase in the years with a high frequency of large rainfall event. If these trends are projected to the future, alternating runoff conditions of drought and flood can be anticipated.

Figure 4 shows variations in daily river runoff during 2002 and 2004. The annual rainfall and the number of the large rainfall events were 733 mm and zero in 2002, and 1415 mm and five in 2004. The nature of runoff is strongly contrasted between these years. In 2002, a flood event with peak runoff in excess of $2000 \times 10^4$ $m^3$ $d^{-1}$ occurred only once. In contrast, peak runoff of this magnitude occurred eight times in 2004, and maximum daily runoff was $17\,000 \times 10^4$ $m^3$ $d^{-1}$. Although the annual rainfall in 2004 was twice that in 2002, the annual runoff in 2004 was ten times that in 2002, and

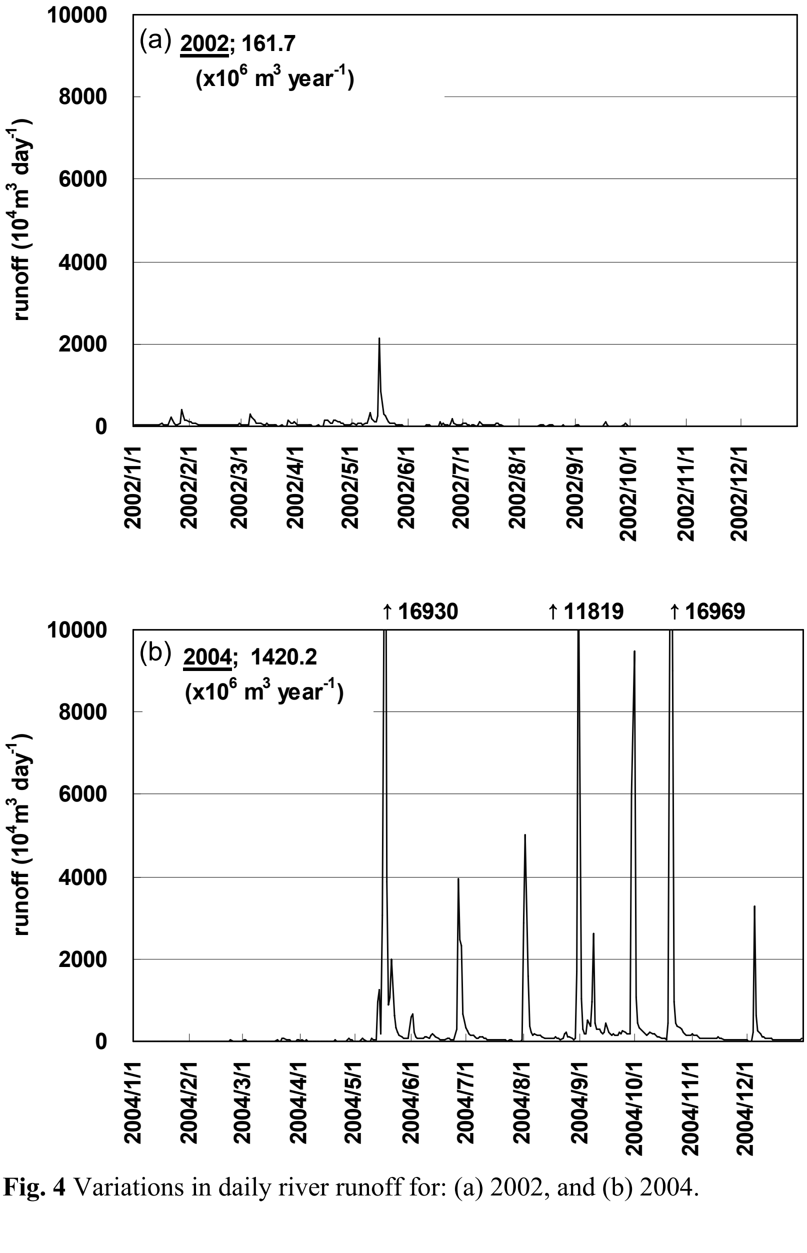


**Fig. 4** Variations in daily river runoff for: (a) 2002, and (b) 2004.

was the largest recorded in the study period. However, most of the runoff in 2004 was a direct discharge component and was unavailable as water resources in the catchment.

## Nutrient discharge in the catchment

The nutrient discharge depends on runoff volume and nutrient concentration. The annual river runoff has decreased by one third with a decreasing trend of annual rainfall in the last 40 years, but the largest annual river runoff is observed once in 10 years with the occurrence of more than four large rainfall events. Consequently, recent climate change has caused contrasting runoff conditions. Since nutrient discharge generally increases with runoff, increasing contrasts between drought and flood years can be expected to increase the variability of nutrient discharge,

Figure 5 shows the nutrient concentration in river water in 1970 and 2001. The value is the average for four years. The DSi and DN concentrations showed the contrasting variation in the long term. The DSi concentration has decreased over the last 30 years, while DN concentrations have doubled since 1970. The DP concentration has been almost constant. The detailed variation is described by Sawano *et al*. (2007). It is suggested that the decrease in DSi has been caused by the trapping in the reservoir constructed in 1990s, similar to that described for the Danube River (Hunborg *et al*., 1997). However, the increase of DN is thought to reflect the increase of domestic wastewater (Sawano *et al*., 2007). In general, it is likely that riverine discharge of nutrients to the ocean will decrease in the long term with the exception of DN that is projected to increase.

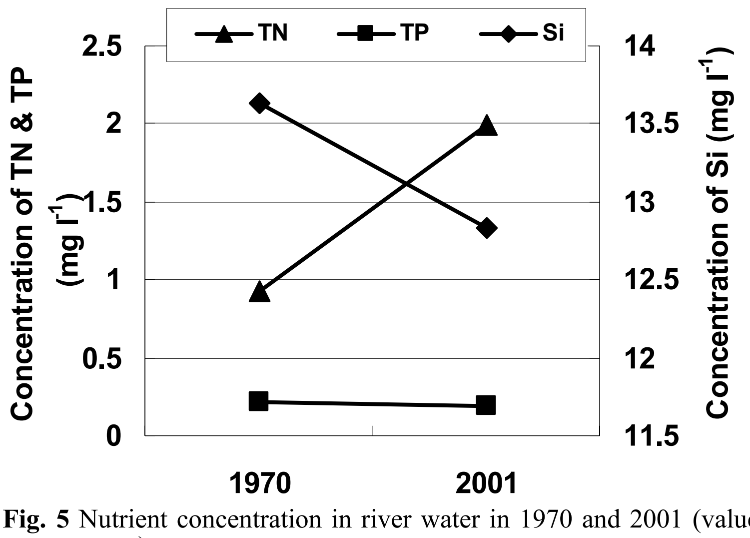


**Fig. 5** Nutrient concentration in river water in 1970 and 2001 (values represent a 4-year average).

The groundwater discharge into the ocean under the delta is estimated from Darcy's law (Freeze & Cherry, 1979). The hydraulic gradient is assumed to be equal to the topographic gradient, because the recharge area is taken to be the river and mountain foot of the upper stream adjacent to the delta, and the water table is near to the ground surface. The sand layer and sand and gravel deposits (Fig. 1) represent the permeable layer with a hydraulic conductivity of 0.05 to 0.1 cm $s^{-1}$. Accordingly, the groundwater discharge was estimated to be 60 mm $year^{-1}$, which is about 5% of annual rainfall.

The estimated amounts of nutrient discharge from groundwater and river into the ocean are shown in Table 1. The ratio of groundwater to river discharge is about 15%. The ratio of DN and DSi contributed from groundwater and river discharge is similar to the ratio for discharge. However, the ratio for DP (>60%) indicates that groundwater contribution is more significant.

**Table 1** Nutrient loads delivered to the ocean through river discharge (RW), and the ratio of groundwater to river transport (GW/RW).

| | Discharge ($10^8$ $m^3$ $year^{-1}$) | TN (t $year^{-1}$) | Si (t $year^{-1}$) | TP (t $year^{-1}$) |
|---|---|---|---|---|
| RW | 3.39 | 645.51 | 5183.082 | 62.097 |
| GW/RW | 15.3% | 19.5% | 14.2% | 67.7% |

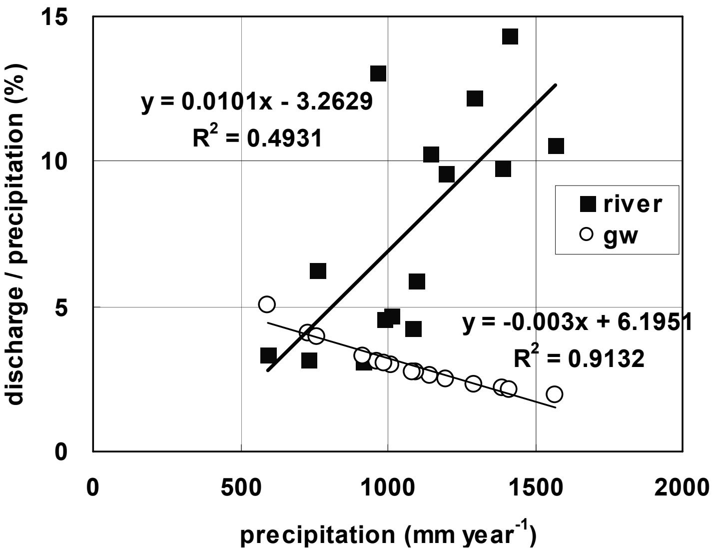


**Fig. 6** Relationships between the ratio of precipitation to discharge and annual rainfall for river flow and groundwater in the period 1988–2003.

## Scenarios for change in nutrient discharge

The river runoff showed a large fluctuation from 20 to 200 mm $year^{-1}$ (Fig. 3), but the groundwater discharge appears to be almost stable, based on the assumption that groundwater level is the same as river water level in the middle reaches. Figure 6 indicates that the ratios between river and groundwater discharge and annual rainfall for the 15-year period since 1988 lie approximately in the range 10–15%. In the study area, evapotranspiration is about 60%. The residual volume is about 30%, which corresponds to the municipal water use. Thus, the river runoff is 15% of annual rainfall in a flood year, but only 3% in a drought year. In a flood year, the river runoff is six to 10 times greater than the groundwater discharge, but in a drought year, the river runoff is lower than groundwater discharge.

The dissolved nitrogen load will increase as the number of large rainfall event increases. Furthermore, the concentration in groundwater is almost same as that in the river, so that the groundwater contribution is also significant. However, previous research has indicated that the nitrate is reduced in coastal groundwater (Howard, 1985; Saito *et al.*, 2005) or in groundwater discharge areas (Ishizuka & Onodera, 1998; Hinkle *et al.*, 2001). Figure 7 shows the relationship between DN and DP concentrations in groundwater and river water, including the potential effect of DN reduction reported in previous research. The present study also suggests that DSi may follow a decreasing trend in the long term, while DP would be increased with increasing groundwater discharge. In flood years, DN load is expected to increase with runoff but DP and DSi loads are expected to decrease, whereas in drought years, the DP is expected to increase.

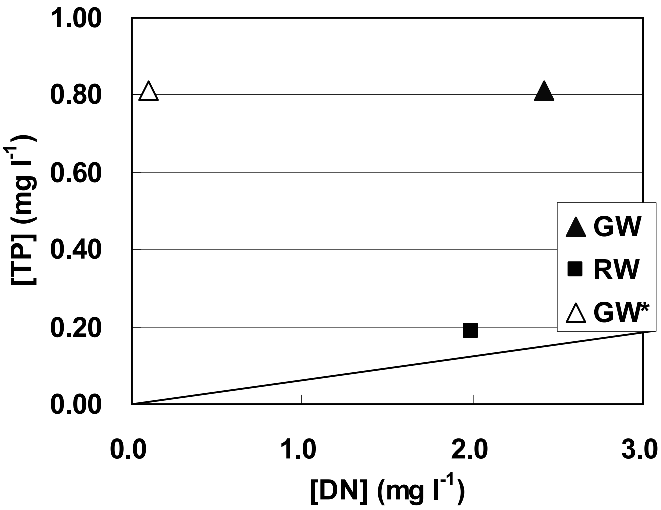


**Fig. 7** Relationship between dissolved nitrogen and phosphorous concentrations in groundwater and river water. (The solid line with a gradient of 0.0625 is the Redfield ratio of plankton and GW* represents concentrations affected by reduction in DN.)

## CONCLUSIONS

In order to forecast how nutrient load discharge to the ocean may vary with climate change, the long term change in rainfall and its effect on river runoff, the nature of nutrient discharge and scenarios for change were determined for the study catchment. A trend of decreasing total rainfall but no decline in the frequency of large rain events was observed over the last 40 years. Consequently, the annual runoff decreased by 60 mm in this period, but the large annual runoff was observed in years with the occurrence of large rainfall events. The nutrient discharge also reflected the rainfall and runoff trends. DN load has increased in the long term, while in drought years DP load has increased, reflecting the dominant groundwater contribution with significantly higher DP concentrations in such conditions.

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