Research article

Water Quality Improvement by Natural Meandering River Surrounded by Woods in Agricultural Watersheds

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Abstract Changes on nitrogen concentration and load of river water during down flow were examined in five rivers flowing through agricultural watersheds in the Tokachi district of eastern Hokkaido, Japan. The upper reach of each watershed is intensively covered by cropland whereas the lower reach is covered by forest. The river form also differs between the upper reaches, which have been artificially straightened by meander cutoff, and the lower reaches, which remain in their natural meandering condition. The lower the reach measured was, the lower the nitrogen concentration was, and this decrease in concentration was even more pronounced in the natural meandering sections than in the straightened sections. The decrease of nitrogen load by natural purification in straightened sections and natural meandering sections was examined using L_{self}, which was introduced as an index of natural-purification-related nitrogen load decrease. In contrast to the changes in concentration, nitrogen load did not decrease in the natural meandering section.

Keywords cropland, straightened river, naturally meandering river, nitrogen, self-purification

INTRODUCTION

River water contamination by agricultural nitrogen has been a serious problem in the Tokachi district of eastern Hokkaido, Japan, where cropland cultivation is the major industry. A survey of river water quality in agricultural areas in the Tokachi district by Tabuchi et al., (1995), Okazawa et al., (2009, 2010, 2011), Woli et al., (2002, 2004) revealed a strong correlation between the proportion of cropland area in a watershed and the concentration of nitrate nitrogen in the river water. They showed that the relationship between the two could be expressed as a linear function. As a result, it is suggested that decreasing the area of cropland as a proportion of the watershed area would be effective in decreasing the nitrogen concentration in the river water; however, such a measure is not realistic because reducing the area of cropland would reduce the agricultural production.

It has been known since ancient times that the water in meandering rivers (i.e. those whose channels have not been artificially straightened) is purified by natural mechanism of self-purification (e.g. Ajayi et al., 1984). It has been proven that, in such naturally meandering rivers, biological, chemical and physical processes eliminate contaminants from the water during the course of the water's flow through the meander sections (Heidenwag et al., 2001).

In formulating river improvement plans for areas whose main industry is cropland farming, improvement of a river's natural ability to purify itself can be an effective way of solving problems in the water environment of the area. Preservation of natural watercourses and the use of construction methods to restore streams (i.e. ecological and near-nature hydraulic engineering) can be effective.

This study reports two years of water quality observations in watersheds in the Tokachi district of Hokkaido. The subject area has croplands at the upper reaches and forests at the lower reaches of its rivers, and we call such an area a "combined agricultural area". We clarified the self-purification ability of the natural streams at the forested lower reaches by observing the degree of natural degradation of the nitrogen components emitted from the cropland field areas at the upper reaches.

METHODOLOGY

Study sites

The subject watersheds are shown in Fig.1. The survey was conducted in the watersheds of seven rivers in the Tokachi district of Hokkaido. The basic data on each river and the watershed are shown in Table 1. The watersheds denoted as PE, PA, UR, PO and PN are those whose upper reaches are mainly cropland fields and lower reaches are forest or pasture. Hereinafter, the subscripts "U" and "L" will respectively denote the upper and lower reaches.

PE_U, PA_U, UR_U, PO_U and PN_U croplands account for 70% to 86% of the total area, which is high percentage. In these areas, the rate of forest is 11% to 27%, and most of the forests are windbreaks for croplands. Potatoes, legumes, wheat, feed corn and sugar beets are the main crops. Cattle farming is also common in these upper-reach areas. Rivers have been converted to drainage canals by straightening of the channels and concreting of the banks.

In areas at the lower reaches (PE_L, PA_L, UR_L, PO_L, and PN_L), the rate of forest is 59% to 94%. Cropland accounts for 6% to 41% of the areas, a large portion of which are pastures of the National Livestock Breeding Center (NLBC). Naturally meandering river channels are preserved in the NLBC.

Watersheds BO and SY are at the NLBC. The rate of cropland is 55% and 63%, respectively, for these watersheds, and most of the area is pasture. The streams in the two watersheds are naturally meandering.

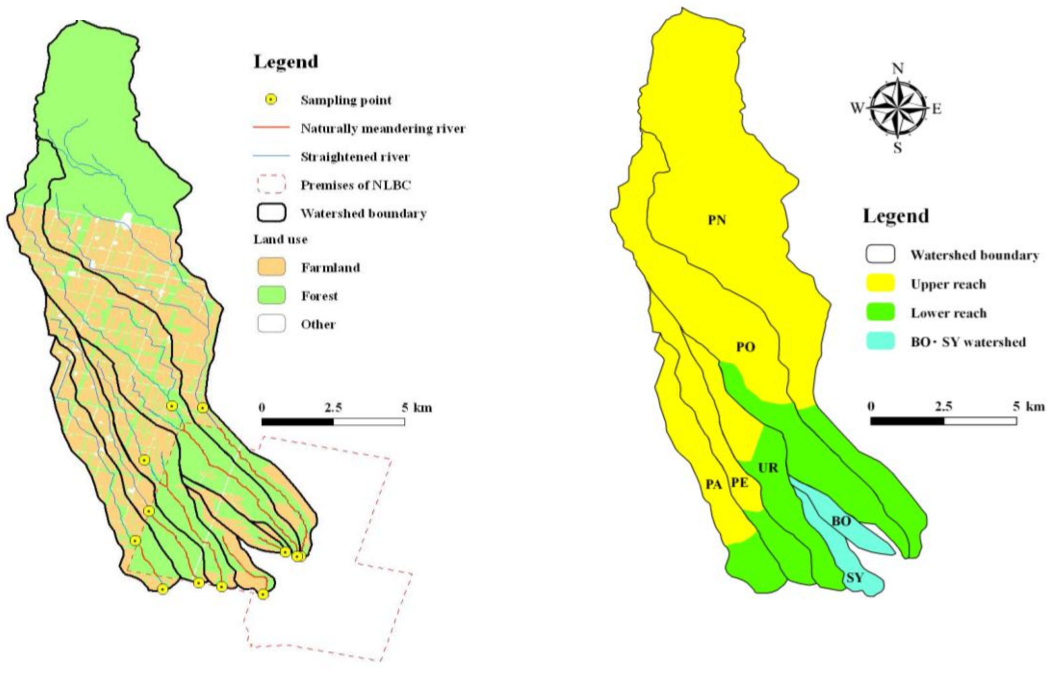


Fig. 1 Location maps of the investigated watersheds

Table 1 Characteristics of investigated watershed

River	Reach	Sampleing point	Area (km^2)	Land use (%) Cropland	Forest	Other	Straightened river (km)	Meandering river (km)	Total (km)	Cattle (Head)	Sample Number
Penkeuretoi (PE)	Upper	PE_1	5.16	83	13	4	7.67	0.00	7.67		21
	Lower	PE_2	2.04	35	65	0	0.58	1.43	2.01		21
	Whole area		7.20	69	28	3	8.25	1.43	9.68	509	
Pankeuretoi (PA)	Upper	PA_1	4.38	84	13	3	8.01	0.00	8.01		18
	Lower	PA_2	2.04	6	94	0	0.00	3.05	3.05		18
	Whole area		6.42	59	39	2	7.96	3.10	11.06	102	
Uranenai (UR)	Upper	UR_1	2.68	85	12	3	3.93	0.00	3.93		19
	Lower	UR_2	4.39	27	73	0	1.59	5.03	6.62		19
	Whole area		7.07	49	50	1	5.59	4.96	10.55	104	
Ponchin (PO)	Upper	PO_1	12.39	70	27	3	14.41	0.00	14.41		9
	Lower	PO_2	6.46	26	73	1	4.90	4.70	9.60		9
	Whole area		18.85	54	43	3	20.41	3.60	24.01	145	
Penkechin (PN)	Upper	PN_1	31.04	33	64	2	17.44	9.48	26.92		18
	Lower	PN_2	3.82	41	59	0	1.34	5.36	6.70		18
	Whole area		34.86	34	61	2	14.46	19.16	33.62	1,079	
Bokujyo (BO)	BO	BO_1	1.82	55	45	0	0.00	0.96	0.96		25
Syuba (SY)	SY	SY_1	2.09	63	37	0	0.00	2.67	2.67		20

*Cropland consist of upland and pasuture.

Hydrological survey method

The survey period was from June to November in both 1999 and 2000. Discharge measurement and river water sampling were done once or twice per month when the rivers were at normal water level. Sampling locations for the watersheds PE, PA, UR, PO and PN are denoted by adding the subscript “1” for upper reaches and “2” for lower reaches. River water samples for each sampling location numbered between 9 and 25.

The items for water quality analysis are total nitrogen (T-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N) and ammonium nitrogen (NH_4-N). Ion chromatography was used to analyze NO_3-N and NO_2-N, and a technique recommended by the JIS was used to analyze T-N and NH_4-N.

RESULTS AND DISCUSSION

River discharge: upper vs. lower reaches

The mean and standard deviation (S.D.) of the river discharge measured at each observation point are shown in Fig.2. The river discharge values at PE, PA, UR, PO and PN are higher for the lower-reach points than for the upper-reach points (significances, $P<0.01$). This reveals that in these watersheds, large amounts of inflow are supplied from areas at the lower reaches of the river.

Comparison of upper-reach vs. lower-reach points in terms of nitrogen concentration

Fig.3 shows nitrogen components measured at each observation point. NO_3-N accounts for 60% to 80% of the T-N at the observation points on the rivers in areas PE, PA, UR, PN and PO. Therefore, the high proportion of NO_3-N in T-N in the river waters in areas PE, PA, UR, PO and PN are attributed to the high proportion of cropland fields in those areas.

Fig.4 shows the mean and standard deviation (S.D.) of T-N in river water sampled at each observation point.

At BO and SY, T-N concentrations are 0.50 mg/L and 0.53 mg/L respectively, which are lower than those of other areas. The values are lower than 1 mg/L, being this value the environmental standard of Japan, based on which it was determined that the water environment of the areas is good. The watersheds of BO and SY consist mainly of forest and pasture.

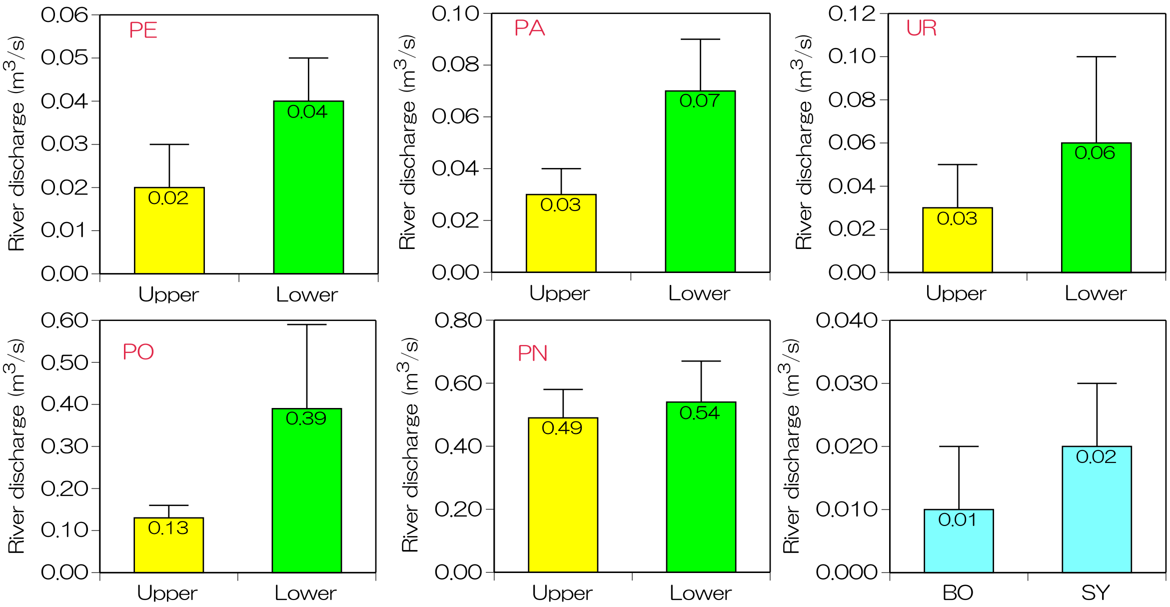


Fig. 2 Mean and standard deviation (error bar) of river discharge for each investigated point

Statistically significant differences (P<0.01) were observed between discharge at upper-reach point and at lower-reach point in the watershed "PE, PA, UR, PO and PN"

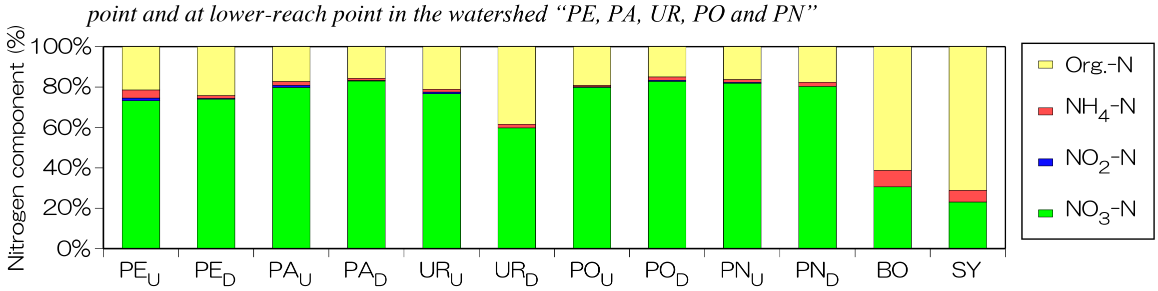


Fig. 3 Percentage of nitrogen components for each investigated point

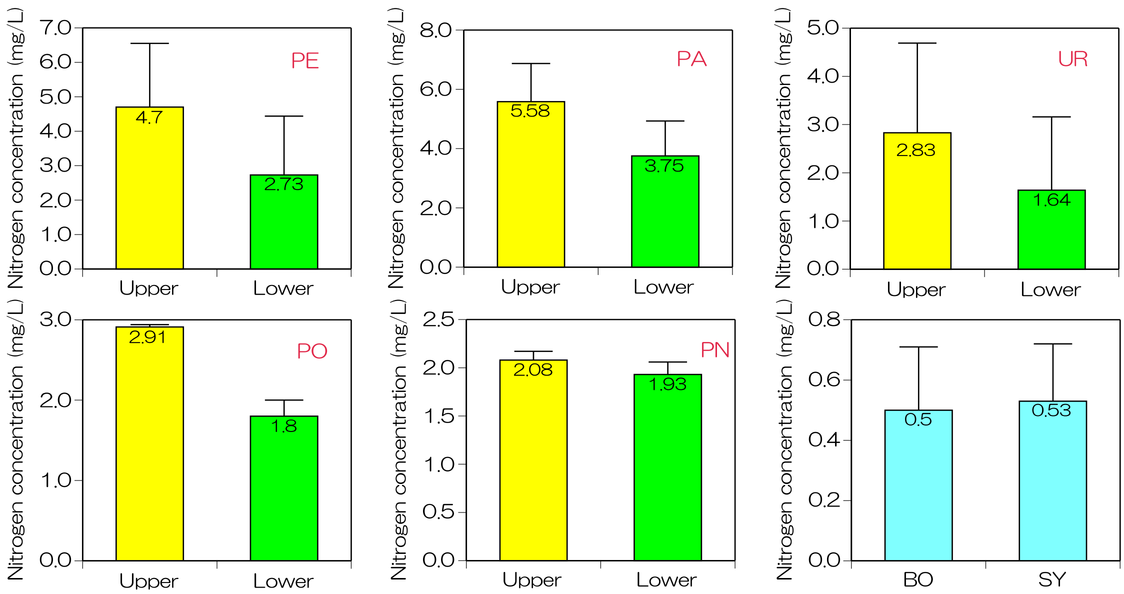


Fig. 4 Mean and standard deviation (error bar) of T-N concentration for each investigated point

Statistically significant differences (P<0.01) were observed between nitrogen concentration at upper-reach point and at lower-reach point in the watershed "PE, PA, UR, PO and PN"

Nitrogen fertilizers are not used in forest or on pasture, and the water flowing from such areas contains only small amounts of nitrogen, which accounts for the low nitrogen concentration in the river water. However, in rivers in areas PE, PA, UR, PO and PN, nitrogen contamination exceeding the T-N environmental standard of 1 mg/L is observed.

When T-N concentrations for the upper and lower observation points of areas PE, PA, UR, PO and PN are compared, T-N concentrations for the lower-reach points are found to be lower than those for the upper-reach points. For each river, the difference in T-N concentration between the upper-reach point and the lower-reach point is significant (P<0.01). The above findings clarify that water high in nitrogen flows from cropland field areas at the upper reaches through rivers to the lower reaches. It was also clarified that the nitrogen concentration of the river water from the upper-reach areas decreases while flowing through the naturally meandering rivers in the forested areas at the lower reaches.

Nitrogen load balance at the lower reaches

The nitrogen balance at the lower reaches is shown in Fig.5. Equations (1) and (2) for nitrogen balance are also shown below. By using these two equations, the self-purification ability (L_{self}) of river at the lower reaches was evaluated.

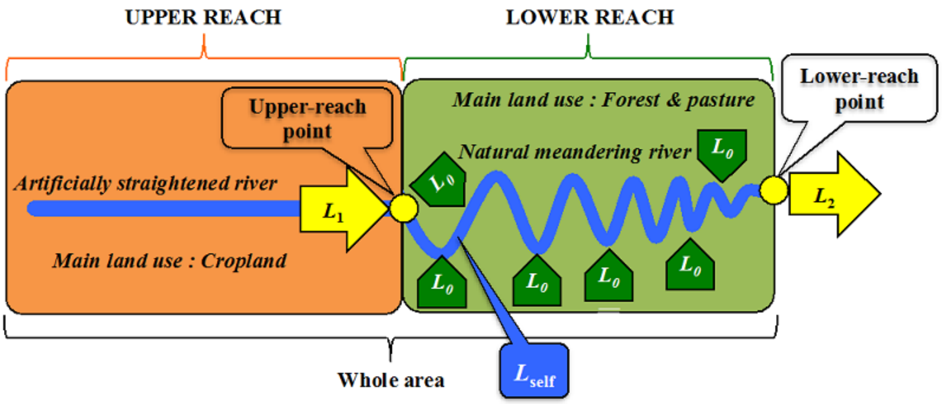


Fig. 5 Concept of nitrogen balance in the combined agricultural area (The watershed "PE, PA, UR, PO and PN")

$$L_2 = L_1 + L_0 + L_{self} \quad (1)$$

$$\therefore L_{self} = L_2 - L_1 - L_0 = (C_2 \cdot Q_2) - (C_1 \cdot Q_1) - [(Q_2 - Q_1) \cdot C_S] \quad (2)$$

L_1 : Load at the upper reaches (g/s)
L_2 : Load at the upper plus lower reaches (g/s)
L_0 : Load from the areas at the lower reaches (g/s)
L_{self}: Self-purification and self-contamination of nitrogen at the river of lower reaches (g/s)
C_1 : Nitrogen concentration at the upper-reach point (mg/L)
C_2 : Nitrogen concentration at the lower-reach point (mg/L)
C_S : Nitrogen concentration in water sampled at the natural river section of the watershed PA (0.75 mg/L, Table 2)
Q_1 : Discharge at the upper-reach point (m^3/s)
Q_2 : Discharge at the lower-reach point (m^3/s)
$Q_2 - Q_1$: Discharge from the lower reaches (m^3/s)

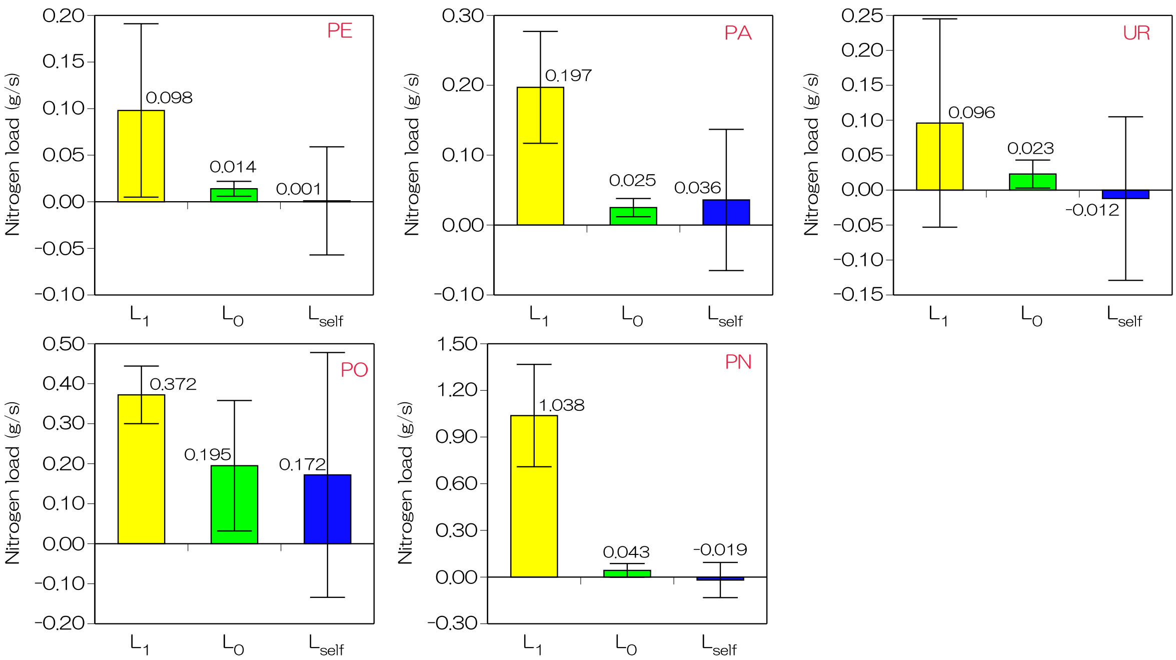
When L_{self}<0, the nitrogen load is purified in the naturally meandering streams; when L_{self}>0, the nitrogen load flows out of the naturally meandering streams. L_0 was obtained by multiplying the surplus discharge at the lower-reach point relative to the discharge at the upper-reach point (Q_2-Q_1) by the mean nitrogen concentration of the water from tributaries that flow into the natural river section (0.75 mg/L, Table 2).

Table 2 Mean nitrogen concentration of inflow water from PA_1 to PA_2

	T-N	NO_3-N	NO_2-N	NH_4-N
Mean	0.75	0.03	0.03	0.00
S.D.	0.40	0.04	0.02	0.00

n=12, 〔mg/L〕

As shown in equation (1), L_2 consists of L_1, L_0, and L_{self}. Fig. 6 shows the mean and standard deviation of L_1, L_0, and L_{self} . L_{self} for each river was smaller than the load from the upper reach (L_1), which means that the total nitrogen load from the upper reaches cannot be totally purified at the lower reaches. The mean L_{self} for rivers in watersheds UR and PN showed negative values, which confirms that the natural sections of these rivers have high purification ability. In all of the surveyed rivers, the standard deviation of L_{self} is greater than the mean L_{self}, because of which L_{self} can take a positive or a negative value. In the naturally meandering sections of the surveyed rivers, natural purification at the lower reaches and nitrogen inflow from land at the lower reaches can occur. Natural purification occurs, but the reduction in nitrogen load is thought to be small.



L_1 : Load at the upper reaches (g/s)
L_0 : Load from the areas at the lower reaches (g/s)
L_{self} : Self-purification and self-contamination of nitrogen at the river of lower reaches (g/s)
If L_{self} is a positive value (+), the nitrogen load flows out of the naturally meandering streams.
If L_{self} is a negative value (−), the nitrogen load is purified in the naturally meandering streams.

Fig. 6 L_1, L_0, L_{self} of mean and standard deviation (error bar) for each river

CONCLUSION

The following was clarified in this study.
1. Water contaminated with nitrogen at high concentrations from the cropland fields in the areas at the upper reaches flows into the natural river sections at the lower reaches.
2. Nitrogen concentration in the river water decreases during the course of the water flowing down to the lower reaches. This is attributed to dilution by abundant inflow of water with low nitrogen concentration from areas at the lower reaches.
3. In a watershed where land use is categorized as “combined agriculture” consisting of cropland fields at the upper-reach areas and forest at the lower-reach areas with naturally meandering rivers,

it was suggested that the nitrogen load supplied from the upper reaches to the lower reaches may be decreased by the river's self-purification ability. It is clarified that nitrogen load is also generated in naturally meandering river sections.

The above findings suggest that naturally meandering rivers are able to achieve self-purification and self-contamination. Future studies should clarify the self-purification mechanisms of naturally meandering rivers. By clarifying the conditions that foster a river's self-purification ability, it is possible to enhance that ability by establishing engineering technologies for conserving river water.

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