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Development of a natural flow hydrological database for PUB studies

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Abstract PUB studies require an accurate hydrological data set of rainfall and discharge either to find standard parameters or to verify non-parameter fitting models. However, ironically, river basins with a good gauge network have usually been developed and therefore flows are almost always altered. A hydrological model cannot predict such arbitrary changes. The Public Works Research Institute of Japan has developed a data set for PUB studies by compiling rainfall data and reconstructing natural flows for the Agatsuma River basin, a tributary of the Tone River in Japan. The data set will be opened up for researchers. Flow data are almost always affected by withdrawals and returns.

Key words Agatsumagawa River; database; natural flow; permitted water right; prediction in Ungauged Basins (PUB); return flow; withdrawal; World Water Assessment Programme (WWAP)

INTRODUCTION

Predictions in Ungauged Basins (PUB) have been a big issue in planning decisions. Small rivers usually have no records of discharge, and flood protection works for a river are planned and designed based on a design flood discharge estimated from the Rational Formula. The Rational Formula can be considered a strong and widely-used PUB technology, although few call it PUB. The drawback of the Rational Formula is apparently its limited applicability, i.e. only to small basins. Therefore, water managers have put a lot of time and effort in to observing discharge in big rivers.

A question raised by World Water Assessment Programme (WWAP: http://www.unesco.org/water/wwap/) is how to assess flood damage or water shortage risks in the world's terrain, most of which is ungauged. To answer the question, the Public Works Research Institute of Japan (PWRI), as a team member of the greater Tokyo case study of WWAP, addressed this PUB problem in cooperation with the University of California at Davis, USA. First, we assumed that we lack not only discharge records but also rainfall records. Second, we decided to take a two-step approach: (a) reconstruction of long-term historical rainfall using only databases that are available worldwide; and (b) reconstruction of flows from the estimated rainfall and worldwide available databases, only.

For reconstruction of rainfall, we took an approach of downscaling re-analysis data using the Integrated Regional Scale Hydrologic–Atmospheric Model (Kavvas *et al.*, 1998). We decided not to use any local databases in spite of their higher accuracy, because our target, an ungauged basin, is likely to lack detailed land use/land cover

Box 1 Input to World Water Assessment Programme

Breakthrough technology for assessing water resources in ungauged basins

PREDICTION IN UNGAUGED BASINS (PUB)

Although the assessment of flood or water shortage risks relies on the ground hydrological network, the network is likened to a newly endangered species. Many parts of the world are losing ground stations, while the others remain completely-ungauged or data-poor. Lack of long-term monitoring results in a decrease in the reliability of risk assessment (Vorosmarty *et al*., 2001). The International Association of Hydrologic Sciences (IAHS) named the research opportunity Predictions in Ungauged Basins (PUB), and launched an international research initiative to encourage scientific research on how to assess water resources in basins with no records.

An opportunity for PUB exists in the assessment of causes of flood risk increase such as in the lower Mekong River. The lower Mekong experienced massive deaths and serious damages by six floods (1991, 1994, 1995, 1996, 2000, and 2001) in the last decade, while it experienced only one, in 1984, in the 1980s. The increased flood damage may be caused by increased frequency of floods due to climate change/variation, landuse/landcover change, or artificial control of water, or by social change such as population increase. Scientific assessment of causes of increased flood damage is the basic knowledge for decision-making, but poor data has prevented assessment. PUB will be the breakthrough technology for providing the knowledge base.

Reconstruction of historical rainfall

PUB technology comprises rainfall prediction as the first step and flow prediction as the second step. The Public Works Research Institute of Japan and the University of California at Davis jointly gave a blind test to downscaling technique in the Greater Tokyo region to reconstruct historical rainfall over the Tokyo area (unpublished). Downscaling requires a sophisticated integrated hydro-meteorological model which requires no parameter fitting, and it is the key technology in PUB (IAHS PUB initiative web site). Assuming the Tokyo region did not have the 17-km mesh ground rainfall network or fine-scale terrain database, NCAR/NCEP reanalysis data have been downscaled by 20-km resolution Integrated Regional Scale Hydrologic Atmospheric Model (IRSHAM) (PWRI, 1997; Kavvas *et al*., 1998) and 6-km resolution MM5 nested in IRSHAM. The advantages of the downscaling approach are: (1) the applicability to any basins in the world without any exception, because all necessary input data can be obtained from world available databases; (2) the availability of reanalysis data from 1948 to present; and (3) the applicability to completely-ungauged basins, while remote sensing always requires a few ground rainfall data.

The blind test to the Tokyo area indicates promising results as shown in Fig.1 and Table 1: Rainfall events are well reconstructed, and annual maximum daily rainfall is well reconstructed.

1995 Observed Generated

May 1

May 2

May 3

0 100km

Fig. 1 Daily rainfall over Tone and Ara River basins (19 501 km^2)

Table 1 Annual maximum daily rainfall over Tone-Ara River Basins.

	Observed	Generated
1994	46.0 mm	50.9 mm
1995	94.3 mm	62.8 mm
1996	89.1 mm	93.0 mm

This reconstruction technology is going to be applied to reconstruct rainfall over the lower Mekong River basin for the last two decades and to scientifically assess frequent-occurring flooding in the last two decades by a Japanese research consortium.

and other necessary data, too. The abstract report shown in Box 1 was submitted to the WWAP Secretariat as input to the World Water Development Report (WWAP, 2003).

For reconstruction of historical streamflows, one needs a no-parameter-fitting hydrology model. No-parameter-fitting means that all the parameters can be derived from existing data or from a practically-feasible survey of the basin's characteristics. A no-parameter-fitting hydrology model can be a completely physically-based model or a conceptual model with standard parameters corresponding to the physical features of the basin like the Rational Formula.

When PWRI made a research plan for reconstruction of streamflows in the Tone and Ara-kawa rivers as part of the greater Tokyo case study, we recognized a problem with the discharge records in our discharge data. Although the Tone and Ara-kawa rivers have relatively good gauging networks, the discharge data are greatly affected by diversions, intakes and returns. No hydrology model can predict artificial effects on flows such as diversions and returns from/to the main stream. Hydrological observation usually starts with the necessity for water development and management. Most of the well-gauged basins have been highly developed: daily flows are used for agriculture, power generation, and urban water supply; and flood waters are partially or largely controlled by reservoirs and diversions. One needs a good data set of natural flows to develop a no parameter-fitting hydrology model for PUB, but it turned out that to prepare natural flow data is a difficult task. This paper describes how we are developing a natural flow data set.

SELECTION OF THE STUDY RIVER BASIN

PWRI has chosen the Agatsukuma River basin of the Tone River system in the Kanto area (equivalent to the Tokyo area) (Fig. 1) for reconstruction of the historical flows for the greater Tokyo case study of WWAP, because the Agatsuma River basin does not have any large dam reservoirs for flood control or water supply. Flow from the Agatsuma River is observed at the Murakami gauging station which has a catchment area of 1365.9 km^2. The catchment area consists of residential areas: 80.1 km^2, dry fields: 22.4 km^2, rice fields: 106.6 km^2, and mountainous areas: 1156.8 km^2. This land cover has been almost stable for many years. The Shinaki dam reservoir on the Agatsuma River basin does not control water flows. It was built to generate hydro-power and mainly to precipitate neutralized products by mixing milk of lime with the naturally highly-acid river flow upper stream. For this reason, the Agatsuma River basin seems to have the least impaired flow of the big rivers in the mountainous regions in the Kanto area. Low lying areas are out of our study scope, even if there are no large dams, because artificial control affects hydrology much greater than mountainous areas in low lying areas, and our target hydrology models for PUB are for mountainous regions.

ESTIMATION OF DIVERSION, INTAKE AND RETURN

Natural flow can be obtained by:

$$Q_n = Q_{obs} + \sum Q_d + \sum Q_i (1 - r_i) \quad (1)$$

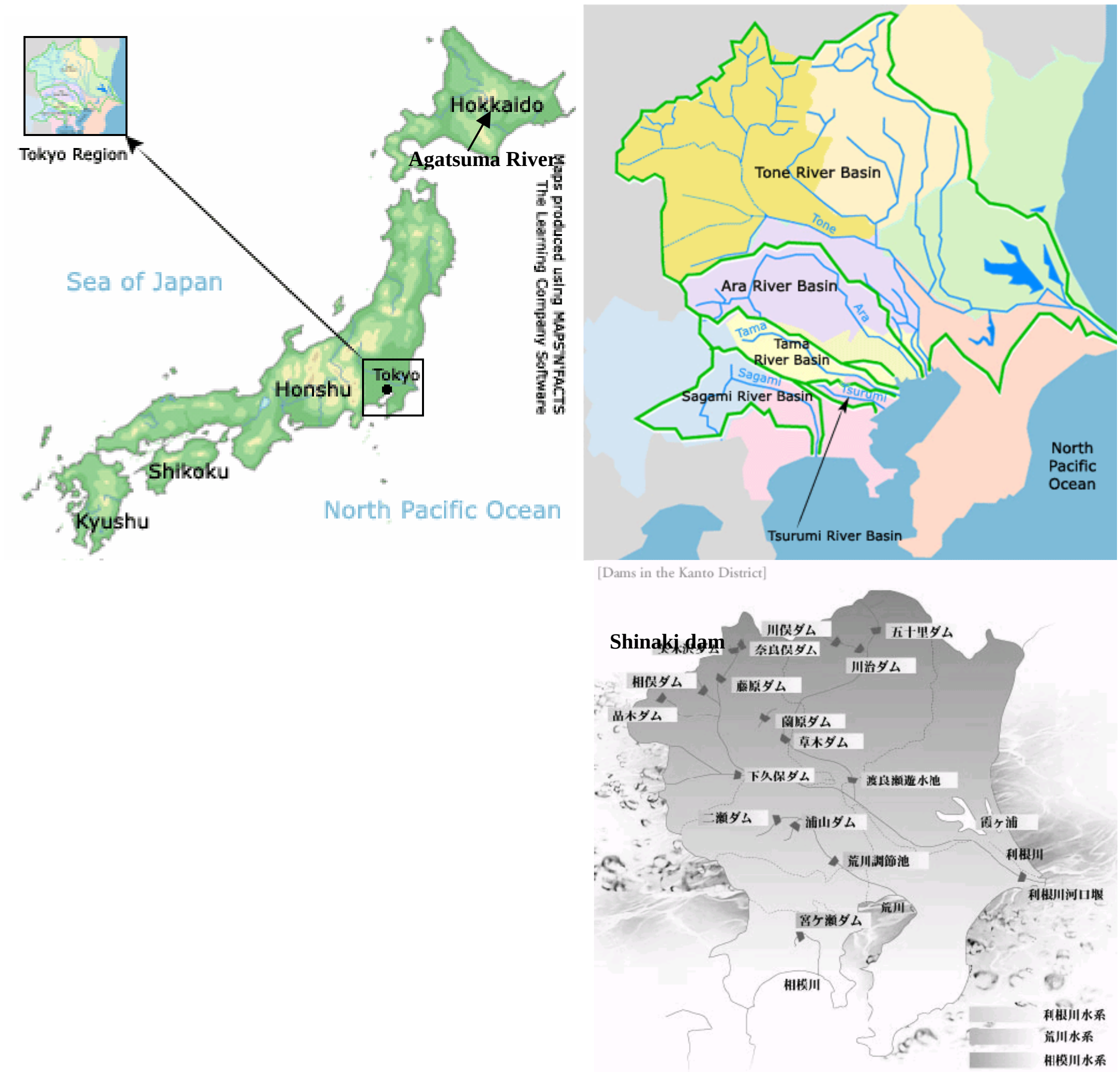

Fig. 1 Location of the Agatsuma River and large dams and reservoirs (The left map shows the location in Japan, the upper right map shows the location in Tokyo area, and the lower right map shows large dams in the Kanto area.)

where Q_n is natural flow, Q_{obs} is observed flow, Q_d is flow diverted but not returned to this basin, Q_i is intake and partially retuned to this basin, and r_i is the ratio of consumptive use as in Fig. 2.

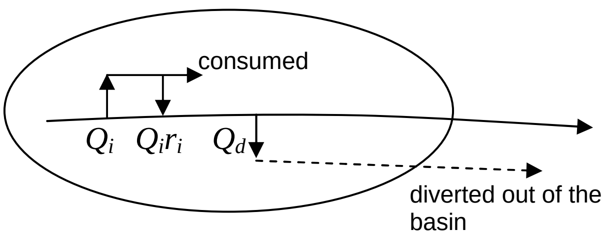

Fig. 2 Conceptual diagram of diversion, intake and return.

The biggest problem is the unavailability of data on water diversions, intakes or returns. Therefore, when data are absent, one needs to use water permits which indicate the maximum water withdrawals. However, when water is running out, actual withdrawals are smaller than permits allow. Therefore, we need to estimate how much water flows at each withdrawal point. In order to do this estimation we need to use a hydrology model subdivided into sub-basins to delineate flows at every withdrawal point. Figure 3 shows the model divisions of the Murakami basin based on withdrawal points. Our model to construct natural flow is the specific discharge method, which assumes that each sub-basin yields the same amount of specific discharge all of the time.

Below we discuss amounts of diversion, intake and return by water use; drinking water supply; industrial use; irrigation; and generation.

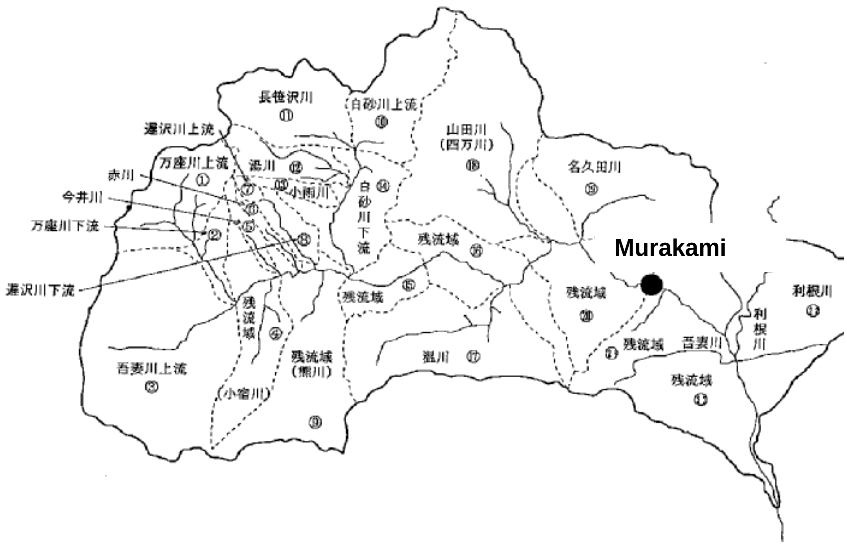

Fig. 3 Division of the basin to estimate flows at withdrawal points.

Withdrawal for drinking water supply The Murakami basin has four withdrawals for water supply. The amount of actual withdrawals is not observed/ recorded. The intake permitted under water rights was considered to be a constant withdrawal throughout the year and no return was assumed. The four permitted water rights total 0.0825 $m^3 s^{-1}$, which is almost negligible.

Withdrawal for industrial use The Murakami basin has six withdrawals for industrial use. The amount of actual withdrawals is not observed or recorded. Intake permitted under water right was considered constant withdrawal throughout the year and no return was assumed. The six permitted water rights total 0.1992 $m^3 s^{-1}$, which is almost negligible.

Withdrawal for irrigation The Murakami basin has 11 withdrawals for irrigation use. The amount of actual withdrawals is not observed or recorded. Intake permitted under water right was considered to be a constant withdrawal throughout the irrigation months from April to August, and a return ratio of 50% was assumed. The eleven permitted water rights total 7.096 $m^3 s^{-1}$, which does influence estimation of the natural flow.

Withdrawal for generation Mountainous regions usually have a lot of generating plants and a lot of water is used for generation to supply electricity to big cities. The Murakami basin has 28 generation plants and 31 withdrawals. The amount of actual withdrawals is observed and reported to the water rights administrator. One of the 23 generation plants diverts water downstream of the Murakami gauging station, while the others return water upstream of the Murakami gauging station, with a 100% return ratio. The water rights permission for diverted water totals 34 $m^3 s^{-1}$, which is considered to have a major influence on estimation of natural flow.

DISCUSSION

The above-mentioned procedure produced a series of estimated natural flows for the 1989–1998 period. An example for 1989 is shown in Fig. 4. This indicates the tremendous discrepancy between observed and natural flows in the daily low flow part and the declining part. The natural low flow is approximately four times larger than that observed, mainly because of water diversions for power generation in this basin, while the total amount of abstraction for irrigation, industry and water supply are negligible.

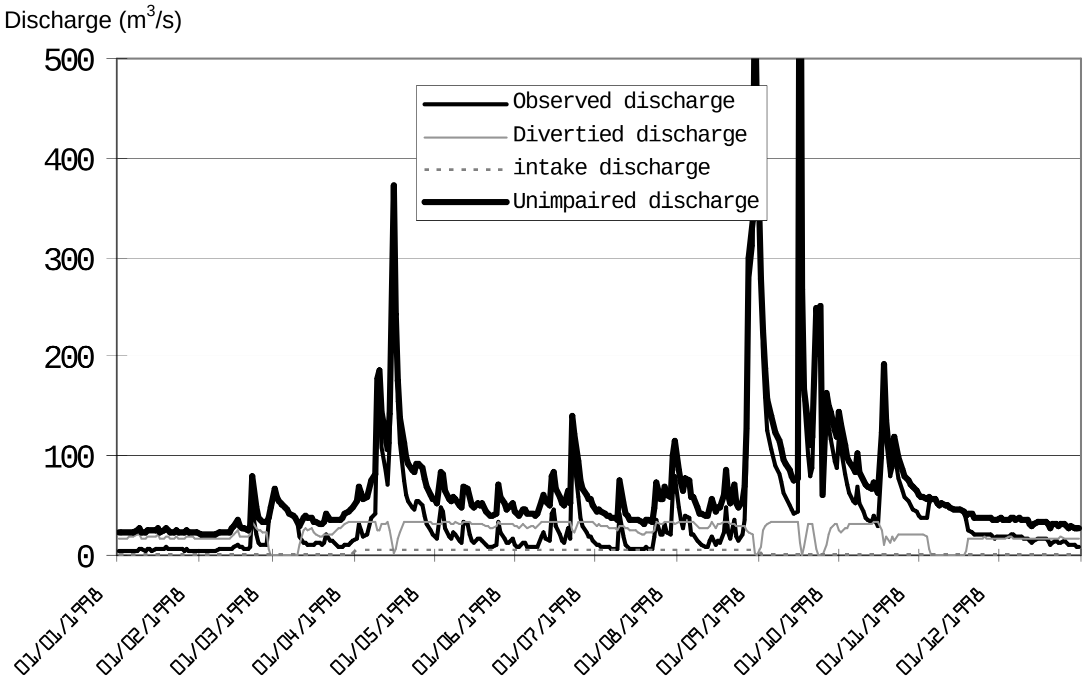

Fig. 4 Estimated natural discharge hydrograph in 1998 at the Murakami gauging station, Agatsuma River, Tonegawa River system, Japan in comparison with observed hydrograph, diverted discharge, and intake discharge

This artificial modification of natural flows cannot be ignored. It is not a special case that flow is greatly altered in well-gauged basins. Looking at the history of hydrological observation, it started because of the necessity of electricity development. Therefore, it seems natural that flow in a well-gauged basin will have been tremendously altered. The use of observed data for hydrological studies will lead to the wrong conclusions and it is important to use natural flow data, i.e. data that replicates the natural situation.

The estimated natural flow data set to promote PUB studies is on the homepage of the International Centre for Water Hazard and Risk Management hosted by PWRI (http://icharm.pwri.go.jp/).

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