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# Use of economic measures for establishing environmental flow in upstream river basins

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**ABSTRACT**
Environmental flow is a hot and current issue in water resources management in many countries in the world. In upstream river basins, it introduces a new constraint to hydropower sector. In the implementation stage of environmental flow economic aspects play a key role in river basin management. Economic measures are useful tools in management because they give strong incentive to conventional water users to change their behavior. We can take advantage of economic measures such as levy and subsidy to achieve consensus among all stakeholders in river basin management.

A subsidy system for setting environmental flow release from hydropower stations is proposed based on a benefit function of environmental flow formulated in terms of flow rate. Under this subsidy, each hydropower station estimates the possible amount of subsidy to compensate the power production loss by flow release. Consequently, environmental flow is determined by optimum decision procedure by each hydropower station. This paper provides decision support system to water resources management in upstream river basins. Economic impact of management policy is large in some regions but not so much in others. We clarify that regional variation of economic impacts is a function of fraction of hydropower in total electric output, hydrological condition, and size of local economy. The subsidy system developed in this study is able to provide an economic measure to mitigate the inequity.

*Keywords*: Environmental flow; hydropower station; environmental tax and subsidy.

## 1 Introduction

River flow is one of the most basic resources for human activities. Water resources management is one of major components of river basin management. Allocation of water is a complex and difficult problem itself, including many stakeholders in its decision making processes. Furthermore, it becomes more complicated when environmental flow participates into the scene as a new water user. Flow regime altered by human needs has caused substantial impacts on riverine ecosystems. Water in rivers is precious resource not only for human beings but also for nature.

Hydropower stations cause reduced discharge in river reaches between intake barrages and outlets. Large amount of flow reduction gives predominant impact in upstream river basins. Environmental degradation caused by flow reduction due to bypassing river flow into aqueducts for human use is now a major concern in many countries in the world. Japanese government issued a guideline for the release of environmental flow in 1988 in order to mitigate the negative impact on riverine ecosystem (Ministry of Construction, 1992). The guideline showed the value of 0.1–0.3 $m^3/s/100\,km^2$ as the standard requirement, and many cases concerning environmental flow release from hydropower stations were settled after 1988 by administrative guidance. Examples of environmental flow in upstream river basins are summarized in Table 1.

Table 1 Examples of environmental flow released from hydropower stations in Japan.

| | Amount of flow released | |
|---|---|---|
| Name | $m^3/s$ | $m^3/s/100\,km^2$ |
| Hidaka | 2.62 | 0.51 |
| Okusaru | 0.22 (Apr.–Nov.) | 0.42 |
| | 0.05 (Dec.–Mar.) | 0.10 |
| Kurodani | 0.42 (May–Oct.) | 0.50 |
| | 0.25 (Nov.–Apr.) | 0.30 |
| Chidori | 0.77 | 0.28 |
| Iwamoto | 1.92 | 0.26 |
| Kuguno | 0.48 | 0.21 |
| Shin-Takatsuo | 2.3 | 0.50 |
| Kannose | 0.47 | 0.30 |
| Shin-Yuyama | 2.1 | 0.52 |

Many methodologies are proposed to set environmental flow requirement. They are classified into four groups: methodologies based on hydrological data, hydraulic rating methodologies,

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habitat simulation methodologies, and holistic methodologies (Tharme, 2000). Most of them are based on pure scientific analyses to obtain "optimal" flow for riverine environment. But when it comes to the stage of implementation, another factor becomes essentially critical – economic aspects. Environmental policy often involves economic loss. It is often the case that conservation of environment is limited to insufficient level because of particular sectors' objections. In those cases, they try to find a point of compromise through political process, which takes time and much effort. We can save those time and effort by using economic measures properly. It would lead to equilibrium point which is acceptable for both of environmental and economic sectors automatically, without troublesome effort for river basin managers.

In this paper, subsidy system is proposed to implement environmental flow policy in upstream river basins. The analysis is developed for hydropower sector, but the same approach can be applied to other sectors such as irrigation and municipal water use.

## 2 A plan of subsidy system for environmental flow

### *2.1 Levy and subsidy as environmental policy measure*

Pigouvian tax is the most basic and ideal type of environmental policy measures. However, it requires too much information to carry out in the real world. Baumol-Oates tax, managing tax ratio to achieve favourable results, is considered to be more realistic. Germany introduced the concept in its water pollution control policy but actually it was arranged as a policy mix with command-and-control. Cost recovering type is even more practical. Water management system in the Netherlands seems to give us a successful example (Andersen, 1999).

Rigorous analysis is important theoretically, but feasibility and cost-effectiveness of the policy is more important practically. Environmental policy is no exception from a rule mentioned above. Levy is preferred than subsidy by theorists because it fits with polluters pay principle. However, subsidy has better acceptability for economic activity sectors. So subsidy is more feasible than levy. They are often mixed together in practice. Moreover, we have to take great care of legal rights, social equity, economic sustainability, and many other things when setting up an environmental policy. Actually we cannot conclude which is better between levy and subsidy before considering those local and social conditions (Rosegrant and Binswanger, 1994).

### *2.2 Subsidy and cost function for environmental flow*

Environmental flow from hydropower stations is released at the sacrifice of power production. However, flow reduction still remains even after release of conservation flow unless all the water used in hydropower station is returned to river. So it is possible for us to raise two opposite opinions. One may say subsidy should be introduced to compensate the economic loss of power production sector. Other may say levy should be introduced to compensate the environmental loss as far as flow reduction remains. The former thinks the present situation as a basis of negotiation, while the latter thinks the original (in other word, completely natural) situation should be a starting point of discussion. Theory in environmental economics tells us that levy and subsidy lead to same result when the levy/subsidy rate is set properly (equivalent to marginal external diseconomies). Same result means same amount of conservation flow, not the same income for power production sector. The choice should depend on social situation of the society. Considering various aspects of the present social situation in Japan, we decided to choose subsidy here.

Amount of levy/subsidy is expressed like this:

$$S(q, L) = k \times I(q) \times L \tag{1}$$

where $S$ = amount of levy or subsidy; $q$ = amount of release from hydropower station; $L$ = section length between water intake (barrage) and outlet; $k$ = constant (levy/subsidy ratio); $I(q)$ = environmental impact caused by flow reduction (in case of levy) or flow release (in case of subsidy).

Magnitude of environmental impact depends on discharge and length of the affected section. It is assumed proportional to the length, but not to the discharge, in Eq. (1). Relationship with discharge is examined later.

Once the subsidy ratio is fixed, each hydropower station tries to determine the optimum amount of conservation flow which maximizes their benefit. We can follow the decision-making procedure by comparing the amount of levy/subsidy given by Eq. (1) and the cost for releasing conservation flow. The cost is calculated as follows.

Economic loss of conservation flow consists of construction cost and power reduction. Construction cost of facilities for release may become considerable in some cases, but most likely release would be done using the existing gates. So, it is neglected in this study. Power supply follows its demand, so power reduction in hydropower stations have to be compensated in other power plants. Additional cost for the compensation is described as:

$$C = g \times Qh \times i \times L \times e \times f \tag{2}$$

where $C$ = additional cost; $g$ = gravity acceleration; $Qh$ = amount of water used as conservation flow; $i$ = channel slope; $L$ = section length between water intake (barrage) and outlet; $e$ = efficiency of water wheel and generator; $f$ = fuel cost for compensating power generation. Note that $Qh$ is the only operational variable for hydropower station manager in Eq. (2).

### *2.3 Determination of subsidy ratio*

Change in discharge affects river environment through many hydraulic components such as velocity, water depth, river width, water level, water mass, and so on. Among these components, river width is selected as an indicator of environmental impact. When we assume triangle cross section whose bottom angle is $2\theta$, Manning's formula gives us the relationship between discharge and water depth as:

$$q = v \times A = \frac{1}{n} \cdot \left(\frac{1}{2}\sin\theta\right)^{2/3} \cdot i^{1/2} \cdot \tan\theta \cdot h^{8/3} \qquad (3)$$

where $q$ = flow rate; $v$ = flow velocity; $A$ = cross section area; $n$ = Manning's roughness coefficient; $i$ = slope; $h$ = water depth at the top of the triangle cross section.

River width is proportional to water depth, so it is proportional to $q^{3/8}$. Therefore, effect of environmental flow is assumed proportional to $q^{3/8}$. Then Eq. (1) becomes like this:

$$S(q, L) = K \times q^{3/8} \times L \qquad (4)$$

This formula will be used to set the amount of subsidy. The coefficient $K$ is determined by environmental flow standard and unit price of environmental impact. They are to be settled by consensus-building procedure in practice. Influence of $K$ value on the result is discussed later in this paper.

## 3 Discussion

### *3.1 Decision making in one hydropower station*

From Eqs. (2) and (4), a hydropower station determines the amount of environmental flow release $q$ as:

$$\frac{dC}{dq} = \frac{dS}{dq} \qquad (5)$$

It brings the largest net revenue for this station.

Capacity of a hydropower station is usually set as in Figure 1. It means that flow release is not needed for 60 days in a year when river flow exceeds the capacity of the hydropower station (New Energy Foundation, 2000). Alternative power source for compensation is supposed to be liquefied natural gas (LNG). Figure 2 shows the decision-making curve for one hydropower station which marginal cost and benefit are compared.

### *3.2 Setting environmental flow standard*

The simplest way to set the standard for environmental flow is to make it just proportional to catchment area (0.3 $m^3$/s/100 $km^2$, for example). It is a practical approach for setting single reference value for large region. But more decentralized method would be preferred in order to address local ecological information. Flow gauging data should be used for this objective. Hydrological characters will be taken into consideration though it is still a simple process. It may lead to more realistic result than using only catchment area. It will be included in the coefficient $K$ in Eq. (4). Natural flow regime must be used to set the standard. Tennant (1976) suggested using a fixed proportion to average annual flow as minimum flow requirement. The method (often referred as Tennant Method or Montana Method) is widely used in North America and European countries. It is a useful tool indeed, but some modification should be done for Monsoon-Asian rivers where flow fluctuation is large. Here we use $Q_{355d}$ method, taking average of 355th largest daily discharge ($Q_{97}$: 97% exceedance value) for each year as environmental flow standard in each river basin. Percentage of the flow to this standard is used as coefficient $K$ in Eq. (4).

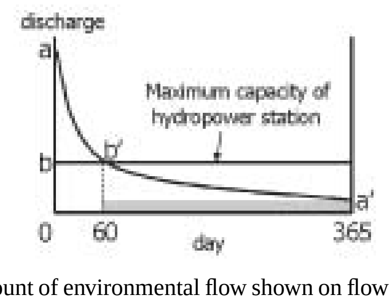


Figure 1 Amount of environmental flow shown on flow duration curve. Dashed area corresponds to environmental flow.

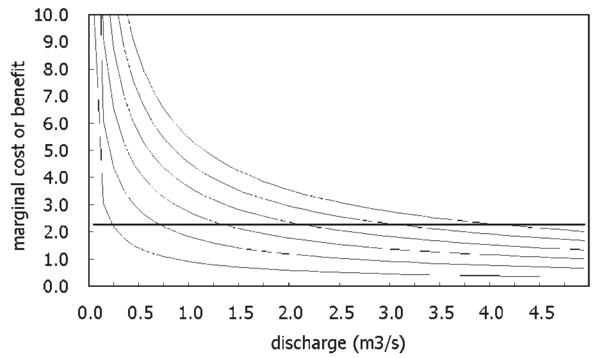


Figure 2 Decision-making curve in one hydropower station. Curves show marginal benefit (subsidy) for different subsidy ratio. Straight horizontal line corresponds to marginal cost. Amount of environmental flow is set at the intersection of benefit curve and cost line.

### *3.3 Analysis of regional characteristics*

Each region has its own economic situation so impact on local economy will vary from region to region. Regional variability of influence on local economy by environmental flow release is discussed in this section.

The country of Japan is divided into 9 regions as shown in Figure 3. Each region is called Region A, Region B, and so on. Table 2 shows components of hydropower stations in each region (Japan Dam Foundation, 2001). Average size of hydropower station is largest in Region F. Region B has many stations but their average size is small, and it is also true for Region D. Region C and F are highly urbanized, densely populated areas. Power demands in these two regions are largest in Japan. Region E is the smallest in terms of power demand. Equation (5) is solved in each hydropower station, and summarized for each region. Coefficient $K$ in Eq. (4) is set in the same way in all the regions. $K$ is set to be proportional to reference flow rate $q_0$, which is brought from average low flow (355th daily discharge in a year) in natural condition in each river. Figure 4 shows the amount of power reduced because of environmental flow release. Reduction is large in region C and F but it doesn't occupy large proportion in those regions because they have large capacity of power plants, mostly fossil and nuclear plants. Region E has the largest reduction rate, almost twice as other regions.

Decision-making curve in one hydropower station. Curves show marginal benefit (subsidy) for different subsidy ratio. Straight horizontal line corresponds to marginal cost. Amount of environmental flow is set at the intersection of benefit curve and cost line.

Additional cost by environmental flow release would raise the power generation cost and thus raise the price of power. Subsidy will compensate the price change. The influence would not be equal in all regions. Occupation ratio of additional cost to total income of local power companies is plotted in Figure 5. It shows the regional variance of impact on local economy. Region E is one of the smallest economic regions but the impact is largest. It is a small and mountainous region with high dependency on hydropower (look at Table 2). Region C has the largest reduction in Figure 4, but the impact is smallest in Figure 5. That's because power production by other sources than hydropower is large in this region, and also size of economy activities is large.

Comparison of Figures 4, 5, and Table 2 shows us some important elements we have to consider from the viewpoint of inter-regional equality. Large hydropower dependence seems to be the most dominant factor for large economic impact, but that is not the only factor. Size of local economy (it governs the scale of power demand and total power production), average size of hydropower station (existence of many small plants leads to large total amount of environmental flow), and hydrological condition are major items which affect the impact on local economy. We have to pay attention to those factors, otherwise some unequal impacts may appear. Subsidy or some other economic measures are one of the answers to avoid such undesirable result.

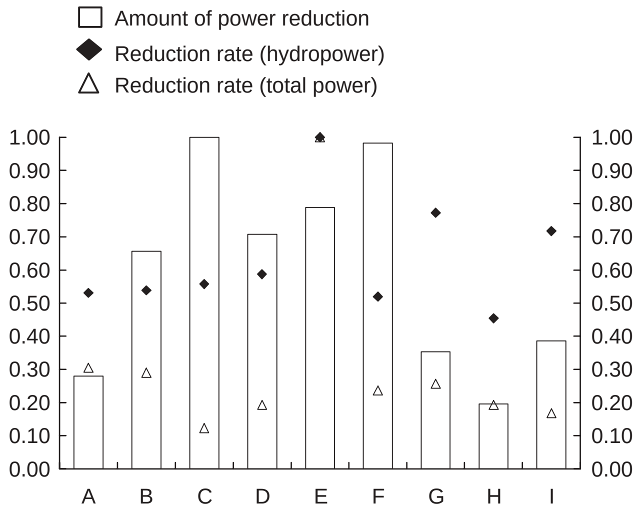


Figure 4 Power reduction by release of minimum flow. Ratio to total capacity of hydropower in each region is also shown. Normalized by the largest value (Region C for power reduction, Region E for the ratio).

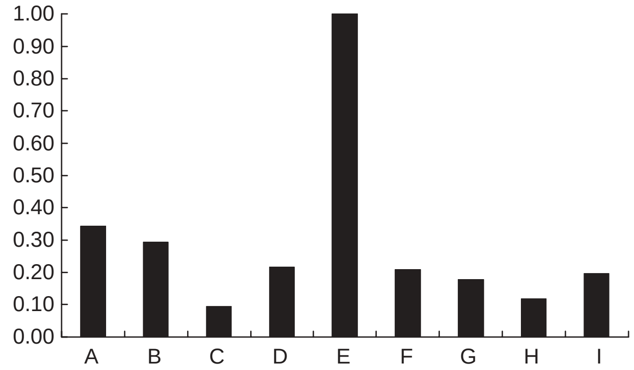


Figure 5 Impacts of environmental flow on local economy. It shows the occupation ratio of additional cost to total income of local power company in each region. Values are normalized by the value of region C.

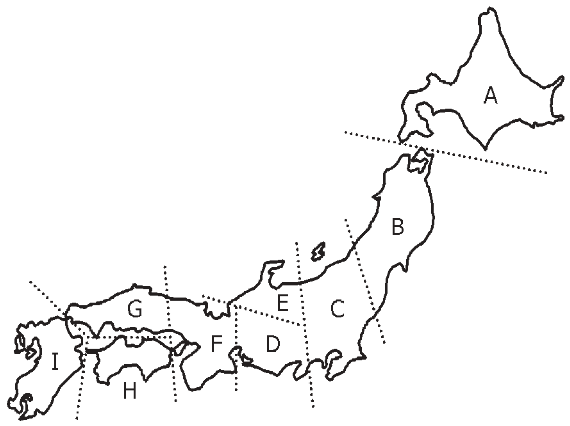


Figure 3 Dividing Japan into 9 regions.

Table 2 Characteristics of hydropower sector in each divided region.

| Region | Power production (billion kWh) | | Hydropower sector | | Average size of one hydropower plant | | Low flow ($Q_{355d}$) |
|---|---|---|---|---|---|---|---|
| | Total | Hydro | Number of plants | Total capacity MW | Catchment area km$^2$ | Capacity MW | m$^3$/s/100 km$^2$ |
| A | 30.00 | 4.03(13.4%) | 57 | 717 | 393.6 | 12.6 | 1.20 |
| B | 74.01 | 9.03(12.6%) | 190 | 1221 | 279.8 | 6.4 | 1.65 |
| C | 265.56 | 13.68(5.2%) | 139 | 1977 | 430.0 | 14.2 | 1.61 |
| D | 119.80 | 9.20(7.7%) | 165 | 1491 | 324.9 | 9.0 | 1.60 |
| E | 25.75 | 6.01(23.3%) | 111 | 1704 | 401.0 | 15.4 | 2.50 |
| F | 135.84 | 14.43(10.6%) | 125 | 2914 | 571.5 | 23.3 | 1.84 |
| G | 44.91 | 3.49(7.8%) | 82 | 728 | 247.6 | 8.9 | 1.14 |
| H | 33.32 | 3.30(9.9%) | 47 | 401 | 165.1 | 8.5 | 1.03 |
| I | 75.11 | 4.12(5.5%) | 133 | 1085 | 187.0 | 8.2 | 1.73 |

## 4 Conclusions

River flow allocation among various sectors including environmental sector is an important element in river basin management. An economic measure, for instance subsidy, will help policy implementation by enhancing its acceptability. We should not overlook the negative impact of human activities on natural environment, but economic interests must not be neglected in the environmental policies, especially in implementing stage. Managers of river basins need economic measures to achieve their goals because economic mechanism is the strongest incentive in many human activities.

A subsidy system for environmental flow is formulated for water resources management in upstream river basins. The subsidy function used in this analysis is primitive and many important aspects are simplified. But the concept can be applied to other regions or other water related problems.

In the latter part, we discussed about the unequal impacts of environmental flow release. Equality is always difficult but important aspect in water resources management. Large effort must be paid to enhance the feasibility of the policy. For environmental flow in hydropower stations, economic impacts are dependent on regional factors of river basins. Subsidy is shown to be an effective measure in water resources management to mitigate the regional inequality. In conclusion a decision support system is developed for water management in upstream river basins considering environmental and economic evaluation of flow regime in upstream reaches.

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