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# Flexible Water Sharing within an International River Basin

D. MARC KILGOUR[1] and ARIEL DINAR[2,*]
[1]*Department of Mathematics, Wilfrid Laurier University, Waterloo Ontario N2L 3C5, Canada;*
[2]*Rural Development Department, The World Bank, 1818 H Street NW, Washington DC 20433, USA*
*(*author for correspondence, e-mail: adinar@worldbank.org)*

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**Abstract.** Increasing scarcity of water resources, and greater variability in available water supply, are causing acute difficulties for allocation agreements among users of water bodies. One cause of controversy, especially for river waters, is the inability of most allocation operations to accommodate variations in conditions. In this paper we develop a flexible mechanism that produces a Pareto-efficient allocation for every possible flow volume in a river. Extensions to accommodate other kinds of variation, such as water demand, are feasible. The mechanism is demonstrated using historical water flow data for the Ganges, based on stylized water demand relationships for India and Bangladesh. Quantitative comparison between fixed and variable allocation suggests that variable allocation substantially outperforms fixed allocation, improving regional welfare by at least ten percent.

**JEL classification:** C78, K33, Q21, Q25

International river and lake basins comprise about 47 percent of the world's continental land area, increasing to at least 60 percent in Africa, Asia, and South America (United Nations 1978; Barrett 1994). Moreover, shared water resources are often essential to countries' economic and social well-being. As the demand for fresh water increases everywhere, it is hardly surprising that international disputes frequently involve the water from shared water bodies.

Historically, river water has often been at the center of international tensions and conflicts. Most of the several hundred international rivers in the world are characterized by borders that separate upstream from downstream countries (Barrett 1994). The unidirectionality of river flow then causes special problems that do not arise for countries that are separated by a boundary river, or for countries that share a sea or lake.

Upstream-downstream disputes have included controversies over operation of the Farakka Barrage on the Ganges (India and Bangladesh) and of the desalination facility near Morales Dam on the Colorado (Mexico and USA), as well as diversion proposals for the Mekong (Thailand and Laos). There is a long history of disputes over the 1929 and 1959 Nile agreements (Egypt, Sudan, and later Ethiopia). (For details, see Vlachos 1990; Barrett 1994; Kirmany and Rangeley 1994; Whittington et al. 1994; Elhance 1999.)

Many principles of international law and diplomacy have been proposed to guide allocation of water within a basin and thereby avoid or resolve international water disputes. (See Beach et al. 2000 Elhance 1999 for a review.) For example, the Law on Non-Navigational Uses of International Water Courses (United Nations 1997) suggests a framework for management and allocation of international waters among users and uses, based on criteria such as equitable and reasonable utilization. Unfortunately, these principles are often difficult to apply and even contradictory, especially for river waters, which constrain transfers because of flow direction, and which exhibit year-to-year – as well as seasonal – variation in flow volumes.

Literature on efficient water sharing agreements among countries within an international river basin is rather limited. Most studies approach the allocation issue via market solutions (Dinar and Wolf 1994), or via cooperation in the form of joint development projects (Rogers 1993). In a recent study, Bennett and Howe (1998) analyze interstate water allocation compacts, focusing on compliance and enforcement. They demonstrate that the likelihood of non-compliance depends on the allocation mechanism (e.g., fixed vs. percentage). In another study, Bennett et al. (1998) examine the economic efficiency of interstate water allocation mechanisms, concluding that a percentage allocation mechanism is likely to be more efficient. However, application of the model to a variable flow regime in the Colorado River yielded results that were either not consistent or not significantly different for fixed versus percentage allocations. None of the above-mentioned papers addresses water quality issues (and neither does this one). Recently, Giannias and Lekakis (1996, 1997) and Lekakis (1998) have applied a model of fixed allocation and quality considerations to the case of the Nestos River shared by Bulgaria and Greece. Their approach (possible only under co-operative arrangements) calls upon bilateral water markets to provide overall efficient solutions using both economic and ecological criteria.

In this paper we introduce the concept of a flexible water allocation rule. This new approach to the economic understanding of the allocation of total river water flows enables us to develop principles guaranteeing efficient (Pareto-optimal) allocations. We also assess the possibility of achieving efficient water allocations in practice, using flexible agreements. Our formal model of water use and other transfers among countries within a river basin depends only on hydrological, geographic, and economic factors. Analysis of the model leads to a characterization of efficient allocations and to algorithms for finding them and determining the associated bargaining problem. One consequence is the concept of “efficient schedule” of river water allocations – a formula that would produce an efficient allocation for every possible level of flow volumes. Requirements for efficient schedules are discussed, and data representing allocations in the Ganges basin are used to illustrate their effects.

*Table I.* Ganges Treaty, 1996: Farakka Barrage water sharing, January–May.

| Flow at Farakka ($m^3$/sec) | India's share | Bangladesh's share |
|---|---|---|
| <70,000 | 50 percent | 50 percent |
| 70,000–75,000 | Balance of flow | 35,000 $m^3$/sec |
| >75,000 | 40,000 $m^3$/sec | Balance of flow |

Source: Adapted from Salman (1997), with permission.

## Addressing Variation in Water Flow: Actual Examples

River flow is characterized by variability. The Ganges, for example, rises from rainfall and glacial melt, and has an average monthly flow ranging from 1789 $m^3$/sec in April, to 43,224 $m^3$/sec in August. (Rogers and Harshadip 1997. These values are monthly averages for the period 1949–1985.) Annual variations in total volume are also significant. At Farakka Barrage, the mean annual flow of the Ganges is 387 BCM (1BCM = $10^9$ $m^3$, with a standard deviation of 73 BCM (London Economics 1994). Such variations are typical: one review suggested that annual fluctuations in river flow of $\pm$25% can usually be attributed to weather; climatic changes and long-term drought events can alter mean annual flow by up to 70% (ILRI 1993). The demand for river water may also change with time, in response to changes in tastes, national priorities, long-term planning, adoption of new technologies, and population growth.

Traditionally, very few water allocations accommodate annual flow variation, let alone long-term trends in demand (Hamner and Wolf 1998; see also the Transboundary Freshwater Dispute Database project website at: http://mgd.NACSE.ORG/qml/watertreaty/). Studies by the UN Food and Agriculture Organization (FAO 1978, 1984) indicate that most of the thousands of current or historical water allocation agreements presume that both water supply and water demand are static (see also Kilgour and Dinar 1995). It is hardly surprising that arrangements in which each riparian receives a fixed supply typically endure only until the first drought.

The Ganges Treaty of 1996 between Bangladesh and India contains an important innovation (Rogers and Harshadeep 1997; Salman 1997). It provides a formula (see Table I) for diversion rates at Farakka Barrage as functions of the flow rate during the dry months. Although this schedule does not consider the allocation of Ganges waters between India and Bangladesh over the entire year, it does represent a flexible approach to resolve, at least in part, the problems of both countries during water shortages.

Another recent example is the 1994 peace treaty between Israel and Jordan. The latter is guaranteed a minimum of 30 MCM/year (1 MCM = $10^6$ $m^3$) from the Jordan River to be supplied during the summer months (Beaumont 1997). As a result of the severe summer drought in 1999, Israel faced difficulties in delivering the agreed-upon amount, and suggested modifying the agreement (GWR 1999). Jordan, of course, insists that the 30 MCM minimum is integral to the peace agreement. This dispute has not yet been resolved (as of mid-1999), and may jeopardize the entire peace treaty.

## River Basin Model

The river basin model used here was developed from the models of Kilgour and Dinar (1995). It focuses on the utilization of river water and the transfer of other resources among the countries within a river basin. For example, it allows a downstream country that needs more water to obtain it from an upstream country by compensating that country for using less water. Note that only water quantities are addressed, and issues of water quality are ignored.

The countries are numbered 1, 2, ..., $n$. To ensure that the model is international, we require that $n \geq 2$. Each country is characterized by its need for water (represented by its water demand function), its contribution to river flow volume, and its relative position in the river basin (that is, which countries are downstream from it).

More specifically, country $i$'s water demand is a function $p_i(\cdot)$, such that if $i$ is already consuming $q_i$ units of water per year, then it would buy additional units at any unit price up to $p_i(q_i)$. A country's water demand function, which treats the country as if it were a single decision maker, is an idealized way to measure its economic value for water.[1] The demand function $p_i(\cdot)$ is assumed to be continuous, strictly decreasing, and strictly positive. (The latter assumption implies that additional water always has a positive value, which may be very small if consumption is already large.) The only information the model requires about a country's value for water is its water demand function. Note that different countries' water consumption amounts [$q$], and water demand prices [$p(q)$], must be measured in identical units. (Sometimes, countries have the option to meet their water demand by purchasing out-of-basin water. Some approaches to modeling this possibility appear in Kilgour and Dinar (1995). Here we assume that all needs for water must be met from the river basin under study.)

A second component of a country's description is its water contribution. Assume that country $i$'s contribution to river flow volume is $Q_i$ units per year. Note that one option available to country $i$ is to consume $q_i = Q_i$ units of water per year. If every country did this, then all river water would be consumed in the country that contributed it, and none would be transferred to other countries. The interest of our model lies in the possibility that some countries may consume less than their flow contributions, and others may consume more.

The third country descriptor represents the relevant geographical facts about the river basin. For each country, $i$, we require the list of countries, $up(i)$, that are upstream from $i$. To analyze the most general river basin model, the logical structure of the $up(\cdot)$ lists must be utilized. We avoid this problem by considering only linear rivers, for which country 1 is the source country [so $up(1) = \emptyset$, the empty set], any outflow from country 1 passes to country 2 [so $up(2) = \{1\}$], then country 3 [so $up(3) = \{1, 2\}$], and so on to the outlet country, $n$ [so $up(n) = \{1, 2, \ldots, n-1\}$].

The identification of upstream countries is important because each country's maximum consumption equals its own flow contribution plus the flow contributions not consumed by upstream countries. Denote all countries' flow contributions by the $n$-vector $Q = (Q_1, Q_2, \ldots, Q_n)$ and their water consumptions by the $n$-vector $q = (q_1, q_2, \ldots, q_n)$. Country 1's inflow is simply $Q_1$. If $i > 1$, country $i$'s inflow is the difference between (1) the total flow contribution of $i$ and all of the countries in $up(i)$ and (2) the total water consumption of all countries in $up(i)$. For convenience, we denote country $i$'s inflow by $In_i(q)$, even though this notation does not show that country $i$'s inflow depends on some of the components of $Q$, and even though country $i$'s inflow is in fact independent of all components of $q$ not associated with countries in $up(i)$.

Thus we define $In_1(q) = Q_1$, and, for $h > 1$,

$$In_h(q) = Q_h + \sum_{k \in Up(h)} Q_k - \sum_{k \in Up(h)} q_k = Q_h + \sum_{k \in Up(h)} (Q_k - q_k)$$

For each country, $h$, annual water consumption, $q_h$, must satisfy

$$0 \leq q_h \leq In_h(q), \tag{1}$$

for $h = 1, 2, \ldots, n$. In fact, equality can be assumed in the last of these weak inequalities, because water demand in the outlet country is strictly positive, so all of the water available to country $n$ will be consumed. Thus,

$$q_n = In_n(q). \tag{2}$$

We have now introduced the quantities – water demand, flow volume contribution, and relative geography – that characterize the countries in the model. We have also indicated how each country's water consumption is constrained by its inflow – its own flow contribution, plus the difference between the flow contributions and water consumptions of upstream countries.

To complete our model of the interrelation of countries in the river basin, we now describe all transfers among them other than water. We model these as simple money transfers. Specifically, each country, $i$, receives an amount $x_i$ from the "pool"; if $x_i > 0$, then country $i$ is a net beneficiary of non-water transfers, and if $x_i < 0$, country $i$ is a net contributor to non-water transfers. Viewing transfers as payments for foregone consumption of water, we require that all transfers balance, i.e.

$$\Sigma_h x_h = x_1 + x_2 + \ldots + x_n = 0. \tag{3}$$

The purpose of the model of money transfers is to allow a country to compensate upstream countries for passing water on to it. Note that pairs of countries may make individual deals – the quantity $x_i$ is simply the net amount, counting receipts as positive and payments as negative, that $i$ receives from all other riparians.

### Schedules of Water Consumption and Compensation

Assume for the moment that countries' water demands, flow contributions, and geographies are known and fixed. A schedule is a specification of the amount of water that each country is to consume, and the amount of money that it is to receive from the pool. Of course, payments to the pool are modeled as "negative receipts."

We do not address issues of equity directly. Our immediate objective is to distinguish among feasible schedules according to their preferability for individual countries and thus to identify efficient (Pareto-optimal) schedules. Where there are many such schedules, we use standard game-theoretic methods to choose one that is representative among those that might result from bargaining, and thus possess some measure of equity. Our overall objective is to show how such a schedule would reflect river basin characteristics – countries' water demands and geographies – and how it might vary according to flow volume.

Formally, a feasible schedule $S = \langle q, x \rangle$ is a pair of $n$-vectors of real numbers, such that the water consumption vector, $q = (q_1, q_2, \ldots, q_n)$, satisfies (1) and (2), and the money receipts vector, $x = (x_1, x_2, \ldots, x_n)$, satisfies (3). Note that the schedule in which each country consumes its own flow contribution and contributes nothing to the pool, namely $q = (Q_1, Q_2, \ldots, Q_n)$ and $x = (0, 0, \ldots, 0)$, is always feasible.

Our objectives at this point are to distinguish among feasible schedules according to their preferability for individual countries, and for the countries of the river basin considered as a group. We also aim to explicate the relationship of preferability of schedules to the characteristics of the river basin – the countries' water demands, flow contributions, and geographies.

How does country $i$ evaluate a schedule, $S = \langle q, x \rangle$? In the first instance, country $i$'s welfare is affected by its water consumption, $q_i$, and its money contribution, $x_i$. Note that we treat each country as an individual decision-making unit that considers only its own well-being and ignores the situation of its neighbors. (We discuss the validity and implications of this assumption later.) We therefore measure a country's total welfare according to its net money receipts plus its consumers' surplus, or

$$W_i(S) = W_i(q_i, x_i) = \int_0^{q_i} p_i(q)dq + x_i.$$

If $W_i(S)$ measures country $i$'s well-being, then it follows that country $i$ *strictly prefers* schedule $S$ to schedule $S'$ if and only if $W_i(S) > W_i(S')$, and is indifferent between schedule $S$ and schedule $S'$ if and only if $W_i(S) = W_i(S')$. Moreover, each country's relative preference can be assessed in this way, making it possible to use the Pareto definitions to define group preference.

Specifically, schedule $S$ is Pareto-superior to schedule $S'$ if and only if $W_i(S) \geq W_i(S')$ for all $i = 1, 2, \ldots, n$, and at least one of these inequalities is strict, i.e. $W_{i^*}(S) > W_{i^*}(S')$, for at least one $i^*$ satisfying $1 \leq i^* \leq n$. Schedule $S$ is Pareto-optimal if and only if there is no other schedule $S'$ such that $S'$ is Pareto-superior to $S$. Schedules that are Pareto-optimal are also called efficient. Our first objective will be to study the properties of efficient schedules.

The theorem to follow describes a fundamental property of efficient schedules. In most cases, an efficient schedule has equal prices for water in every country, because otherwise water could be transferred from a country where the price is low to a country where the price is high, in return for a suitable payment. (We assume that the conveyance cost of running water from an upstream country to downstream country is zero.) But practical considerations may prevent this transfer; one restriction is that countries cannot consume less than zero, so foregoing consumption altogether is the most a country can do to transfer water elsewhere. Other restrictions, (d) and (e) in the theorem below, reflect the consequences of the unidirectionality of river flow.

Recall that we are assuming a linear geography, so country $i$ is upstream of country $j$ if and only if $i < j$.

**Theorem:** Let $S = \langle q, x \rangle$ be an efficient schedule, and let $i$ and $j$ be any two countries, where $1 \leq i < j \leq n$. Then exactly one of the following statements is true:

(a) $p_i(q_i) = p_j(q_j)$.
(b) $p_i(q_i) < p_j(q_j)$ and $q_i = 0$.
(c) $p_i(q_i) > p_j(q_j)$ and $q_j = 0$.
(d) $p_i(q_i) > p_j(q_j)$ and $q_i = In_i(q)$.
(e) $p_i(q_i) > p_j(q_j)$ and for some $k$ such that $i < k < j$, $q_k = In_k(q)$.

*Proof:* For a feasible schedule $S$ and two countries $i$ and $j$ with $i < j$, assume that (a) is not true. We show that a schedule $S'$ that is feasible and Pareto-superior to $S$ can be constructed unless either (b), (c), (d), or (e) holds.

First, assume a schedule $S$ at which $p_i(q_i) < p_j(q_j)$ and $q_i > 0$. Pick $\varepsilon > 0$ such that $\varepsilon < q_i$ and $p_i(q_i - \varepsilon) < p_j(q_j)$. Let $\delta = \varepsilon\, p_i(q_i - \varepsilon)$. Define schedule $S'$ to be identical to $S$ except that $q'_i = q_i - \varepsilon$, $x'_i = x_i + \delta$, $q'_j = q_j + \varepsilon$, and $x'_j = x_j - \delta$. To verify that $S'$ is feasible, note that (3) holds for $x'$, and that (1) holds for $h = i$ because $0 < q'_i < q_i$. If $k = i + 1, i + 2, \ldots, j$, $In_k(q') = In_k(q) + \varepsilon$, so (1) [and, if appropriate, (2)] holds for $h = k$ as well. Since $S$ and $S'$, and the feasibility conditions, are identical for all values of $k$ less than $i$ or greater than $j$, it follows that $S'$ is feasible.

We now show that $S'$ is at least as preferred as $S$ for $i$, and strictly preferred for $j$. First,

$$W_i(S') - W_i(S) = \delta - \int_{q_i-\varepsilon}^{q_i} p_i(q)dq \geq 0,$$

because $\delta = \varepsilon p_i(q_i - \varepsilon)$. Moreover,

$$W_j(S') - W_j(S) = \int_{q_j}^{q_j+\varepsilon} p_j(q)dq - \delta \geq \varepsilon(p_j(q_j) - p_i(q_i - \varepsilon)) > 0.$$

This completes the proof that $S'$ is Pareto-superior to $S$, so $S$ cannot be Pareto-optimal. Thus if $S$ is Pareto-optimal schedule and $i$ and $j$ satisfy $i < j$ and $p_i(q_i) < p_j(q_j)$, then (b) must hold.

Now assume a schedule $S$ at which $p_i(q_i) > p_j(q_j)$, $q_j > 0$, and, for all $k$ satisfying $i \leq k < j$, $q_k < In_k(q)$. Pick $\varepsilon > 0$ such that $\varepsilon < q_j$ and $\varepsilon < In_k(q) - q_k$ for $k = i, i+1, \ldots, j-1$, and $p_j(q_j - \varepsilon) < p_i(q_i)$. Let $\delta = \varepsilon p_j(q_j - \varepsilon)$. Define schedule $S'$ to be identical to $S$ except that $q'_i = q_i + \varepsilon$, $x'_i = x_i - \delta$, $q'_j = q_j - \varepsilon$, and $x'_j = x_j + \delta$. As above, it is easy to verify that $S'$ is a feasible schedule. To show that $S'$ is Pareto-superior to $S$, note that

$$W_j(S') - W_j(S) = \delta - \int_{q_j-\varepsilon}^{q_j} p_j(q)dq \geq 0,$$

because $\delta = \varepsilon\, p_j(q_j - \varepsilon)$. Moreover,

$$W_i(S') - W_i(S) = \int_{q_i}^{q_i+\varepsilon} p_i(q)dq - \delta \geq \varepsilon(p_i(q_i) - p_j(q_j - \varepsilon)) > 0.$$

This completes the proof that if $S$ is a Pareto-optimal schedule and $i$ and $j$ satisfy $i < j$ and $p_i(q_i) > p_j(q_j)$, then one of (c), (d), or (e) must be true. $\square$

To summarize the Theorem, at any efficient schedule the price for water is the same in every country, except that the price can differ between a pair of countries for which condition (b), (c), (d), or (e) makes water transfer impossible using according to the adjusted schedule described in the Theorem. Observe that the only restriction on downstream transfers is that (b) cannot hold. Upstream transfers are possible only when the initial distribution avoids all of (c), (d), and (e).

We interpret (d) and (e) as consequences of the nature of river flow. For the sharing of lake water among riparians, a parallel theorem would show that either prices are equal in each pair of countries, or a condition like (b) or (c) applies. Thus, the features of the Theorem that reflect the relationship of river riparians are (d) and (e). They represent structural barriers to upstream transfers of water.

To be specific, a downstream transfer is always possible, providing the upstream partner does not run out of water (i.e. (b) holds). But an upstream transfer may be impossible if (c) the downstream partner runs out of water, (d) the upstream partner is already consuming its total inflow, or (e) some intermediate riparian is already consuming its total inflow. Thus, conditions (d) and (e) are fundamental to rivers. We caution that we have considered only a linear river; another obvious restriction on all transfers is that the provider and the recipient must share the same branch of the river – i.e. one must be downstream of the other.

## Efficient Levels of Water Consumption

We conjecture that a consequence of the Theorem is that every efficient schedule corresponds to the same water consumption vector, $q$. As will be shown below, this fact is not difficult to demonstrate in the cases $n = 2$ and $n = 3$. Of course this efficient consumption vector $q$, assuming it exists, depends on the geography, the water demands, and the flow contributions. In particular, a procedure can be found that – at least in the simple cases discussed below – permits the recalculation of the efficient water consumption vector each year, as soon as the flow contributions become known. Below we discuss the implications of such a recalculation.

### EFFICIENT WATER CONSUMPTION: TWO COUNTRIES

For a river basin that comprises only two countries, the consequences of the Theorem are easy to work out. There are essentially only three possibilities for the efficient water consumption vector $q = (q_1, q_2)$; they are set out below in a way that emphasizes their dependence on the underlying parameters.

(b) $q_1 = 0$, $q_2 = Q_1 + Q_2$ occurs whenever $p_1(0) \leq p_2(Q_1 + Q_2)$;
(c) $q_1 = Q_1$, $q_2 = Q_2$ occurs whenever $p_1(Q_1) \geq p_2(Q_2)$;
(a) $0 < q_1 < Q_1$, $Q_2 < q_2 < Q_1 + Q_2$ occurs otherwise.

The letters at the left of the three cases above correspond to the conditions in the Theorem for $i = 1$ and $j = 2$, which is the only possible choice. For convenience in expressing the existence conditions, the cases are not listed in the same order as the Theorem. Observe that the water prices in the two countries are equal, $p_1(q_1) = p_2(q_2)$, if and only if case (a) applies.

Figure 1 shows the set of possible combinations, $(q_1, q_2)$, that represent efficient water consumption vectors. Observe that all possible combinations satisfy $q_1 + q_2 = Q_1 + Q_2$. Country 2, the downstream country, always consumes its own flow contribution, $Q_2$; the question is, how much of $Q_1$ does it consume also? Note that the thicker line in Figure 1 represents all water consumption vectors that are efficient in the Pareto sense.

### EFFICIENT WATER CONSUMPTION: THREE COUNTRIES

The efficient water consumption vector for a linear river basin containing three countries can be calculated similarly to the two-country case. The possibilities for

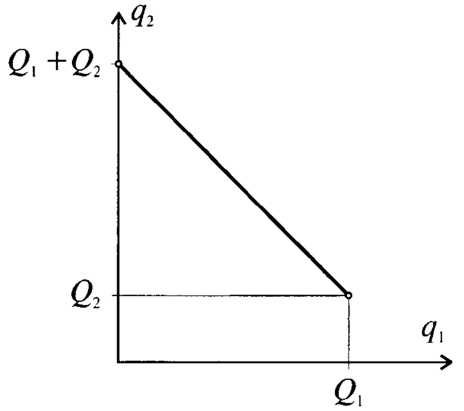


*Figure 1.* Two country efficient water allocation possibilities.

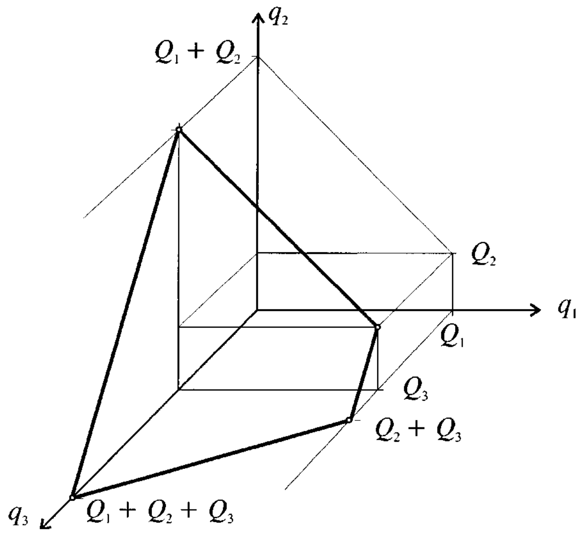


*Figure 2.* Three country efficient water allocation possibilities.

$(q_1, q_2, q_3)$ are represented by the points of the oblique plane with thicker edges in Figure 2.

If the consumption vector $(q_1, q_2, q_3)$ is a point in the interior of this plane, then at the efficient consumption schedule, $p_1(q_1) = p_2(q_2) = p_3(q_3)$. Again, note that $q_3 \geq Q_3$, and that $q_1 + q_2 + q_3 = Q_1 + Q_2 + Q_3$. Beginning at any schedule not on the plane shown, another schedule preferable to all three countries can be found that includes a consumption vector in this plane.

**Bargaining over Compensation**

So far we have discussed only the consumption vector at an efficient schedule. To identify the efficient schedules, $S = \langle q, x \rangle$, we must also specify the possible compensation vectors, $x$. In fact, the fundamental determinant of the compensation vector is institutional: Who owns the water? The possibilities for compensation vectors at efficient schedules are determined by ownership and by the optimal consumption vector, which is conjectured above to be completely determined by the circumstances.

The description given here of determination of the compensation vectors that are consistent with optimal schedules generally follows the procedure of Kilgour and Dinar (1995). The two-country case is relatively simple, as the relevant variables can be drawn in two dimensions as in Figure 3. Note that $q_2 = Q_1 + Q_2 - q_1$ and $x_2 = -x_1$, so that the variables $q_1$ and $x_1$ shown in Figure 3 do in fact completely determine a schedule $S = \langle (q_1, q_2), (x_1, x_2) \rangle$.

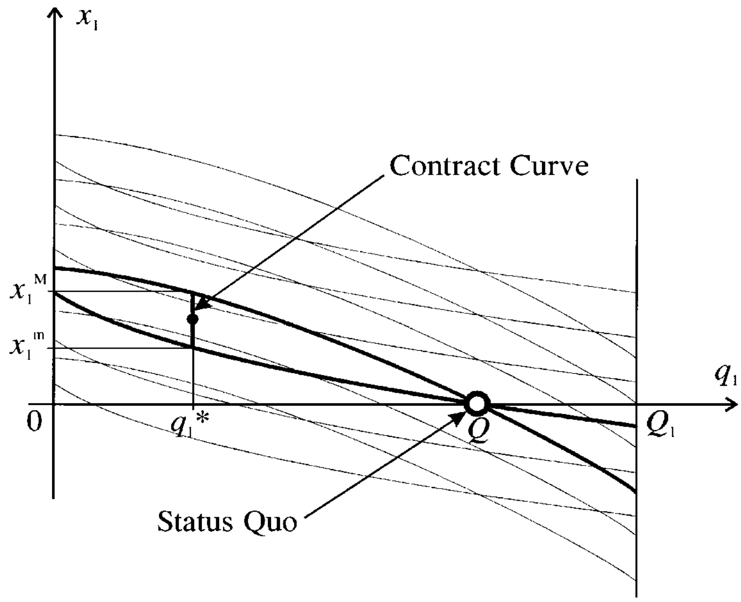


*Figure 3.* Indifferent contract curves.

The Status Quo schedule, $S_0$, represents the situation wherein each country consumes the water it "owns," or has the right to consume, and no compensation is paid. This situation is represented by the point $(Q, 0)$ shown in Figure 3, where $Q$ is the amount of country 1's flow contribution that 1 has the right to consume. Thus, $S_0 = \langle (Q, Q_1 + Q_2 - Q), (0, 0) \rangle$. Note that $0 \leq Q \leq Q_1$, i.e. we assume that a country never has the right to consume water from the flow contributions of downstream riparians. Different conceptions of ownership represent different values of $Q$.

The curves shown in Figure 3 are indifference curves – those that bend downward to the right are indifference curves for country 2, and those that bend upward to the left are indifference curves for country 1. (A country is indifferent between any two points on an indifference curve. Note that a country's indifference curves never intersect, and that every point lies on exactly one indifference curve.) Country 1 always prefers a higher indifference curve and country 2 always prefers a lower indifference curve.

It follows that the two primary indifference curves, passing through the Status Quo, are important because the points above country 1's curve and below country 2's (to the left of the Status Quo in Figure 3) are preferred by both countries to the Status Quo. More specifically, any schedule, $S$, corresponding to a point in this region satisfies $W_1(S) \geq W_1(S_0)$ and $W_2(S) \geq W_2(S_0)$.

When so many schedules are available, which is best? It turns out that the efficient water consumption vector corresponds to the value of $q_1 = q_1^*$ where the separation of the primary indifference curves is a maximum. (It is possible to argue directly that this maximum separation characterizes an efficient schedule – see Kilgour and Dinar (1995), for details.) The line joining the points of maximum separation of the two primary indifference curves is called the Contract Curve. This construction is related to the well-known Edgeworth Box construction, and to the von Neumann-Morgenstern Stable Set.

In two-country river basins, the complete set of efficient schedules can be determined in this way. As shown in Figure 3, an efficient schedule satisfies $q_1 = q_1^*$, as determined by the Theorem, and $x_1^{\mathrm{m}} \leq x_1 \leq x_1^{\mathrm{M}}$. (Recall that this is a complete specification of the schedule, as the values of $q_2$ and $x_2$ are functions of $q_1$ and $x_1$.)

Thus, the level of compensation in the two-country river basin problem is a bargaining problem that is not strictly determined by the geographic and economic conditions and the prevailing institutional arrangements. Standard cooperative game theory models can be applied to this bargaining problem; they produce a specific prescription for an efficient schedule. For the "two-person" bargaining problem, virtually all of these methods yield the midpoint of the contract curve, highlighted in Figure 3.

In the case of a linear river with $n = 3$ countries in its basin, the situation is more complex. However, an illustration of the explicit determination of an efficient schedule is available. Kilgour and Dinar (1995) carried out this calculation using some demand functions of a specific form, along with the assumption that $Q_1 > 0$, $Q_2 = Q_3 = 0$. In this case, the contract curve becomes a (two-dimensional) contract set – three instances of this contract set, corresponding to different values of $Q_1$, are shown in Figure 4. Within each of these contract sets, the prescriptions of the two cooperative game theory solution methods, Nash Bargaining Solution and Shapley Value, coincide and are shown in the figure.

To explain Figure 4, note that the shaded triangles represent all feasible combinations of amounts paid by country 2 (the negative direction on the vertical axis) and by country 3 (the negative direction on the horizontal axis). The fact that each triangle has a 45° line as its upper right-hand boundary indicates that there is a minimum total compensation to be received by country 1. For very low

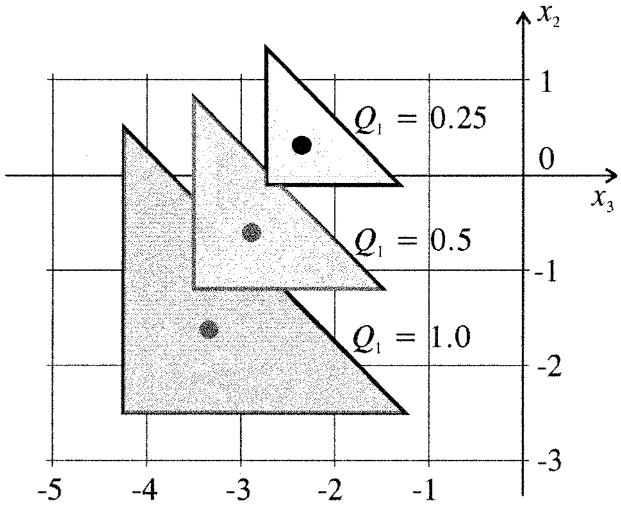


*Figure 4.* Bargaining possibility zones for various values of annual flow (*Q*).

values of the total flow, efficient schedules call for country 2 to forego most water consumption and to be compensated by country 3. At higher levels of the total flow, country 2 consumes a larger fraction of the water it receives, and tends to make a payment to country 1. Country 3 always compensates country 1; in this model, it has a high demand for water, and no source of its own.

**Variable Schedules: Information Requirements**

We now turn to perhaps the most interesting and surprising aspect of this study: At any efficient schedule, the levels of water consumption of the countries in a river basin are completely determined by the underlying geography, economics, and flow contributions, and cannot be bargained upward or downward if efficiency is to be preserved. (Of course, the compensation vector must be determined somehow; our theory is silent as to how that is to be carried out in the absence of adjustments in water consumption amounts.) It is anticipated that further development based on the Theorem will produce an algorithm to determine these efficient water consumption levels.

Such a procedure would permit the achievement of a new level of efficiency in water basin management. Taking geography and water demand as constant, all that is required to determine efficient water consumption levels is flow contribution. If annual flow contribution can be predicted accurately in advance, then a formula can be developed to generate (what we conjecture to be) the unique efficient schedule consistent with the conditions in the basin. In fact, changes in water demand can even be included in this calculation, if they are understood and agreed upon in advance. Thus, the theoretical developments described above indicate the possibility of flexible and efficient water sharing agreements – contingent, of course, on accurate predictions of annual flow volume.

Fortunately, new technology can provide this information in an accurate, timely, and credible manner. In the near future, data on water levels, etc., for many important international rivers will be gathered by remote sensing and satellite-based methods and made available publicly, permitting flow volumes and withdrawal rates to be calculated (World Bank et al. 1993). In consequence, accurate forecasts of annual flow volumes will become available to all riparians, along with knowledge of all countries' withdrawal rates.

Improved credibility may be the most important result of this new information. It is well known that agreements without active enforcement are unlikely to succeed (Kilgour 1993). The availability of accurate one-year forecasts will eliminate any risk of the stochastic nature of the flow being used to conceal unauthorized withdrawals. Transparency as well as efficiency will be achieved when allocations are publicly modified each year to ensure that they are precisely fair, or welfare-maximizing, rather than, at best, possessing these properties "in an average year."

Annual adjustment of allocations would certainly be welcome. Any water-sharing scheme that accounts for the stochastic nature of water supply and the dynamic nature of water demand will almost certainly be more stable. Instabilities are now a particularly acute problem for rivers in which most of the flow is consumed in most years. In addition, the ability to vary allocations depending on current conditions may reduce regional water-allocation transactions costs, allow countries to plan their water-related investments more effectively, increase regional social welfare, and reduce regional tensions.

## VARIABLE SCHEDULES: EXAMPLE

A data set (London Economics 1994) consisting of 37 observations of the annual flow volume, from 1949 to 1985, in the Ganges at Farakka was used to simulate the effects of a variable schedule in a river basin with $n = 2$ countries. The water demands of India and Bangladesh at Farakka were represented by notional demand functions of the exponential form used by Kilgour and Dinar (1995),

$$P_i(q_i) = C_i e^{-c_i q_i}$$

where $C_i$ and $c_i$ are coefficients in demand functions for India and Bangladesh.

Using these demand functions, the total welfare in the basin, $W(S) = W_1(S) + W_2(S)$, could be calculated for any schedule, $S$. Note that $W(S)$ does not depend on the compensation vector, $x$, because of (3). The objective was to compare the two different allocation schedules: (1) the flexible efficient schedule, in which each year's consumption vector is efficient, and (2) the 'optimal' fixed schedule, in which the allocation to the upstream country (India) was fixed at the efficient allocation in a year with exactly the average flow – the balance of the flow was

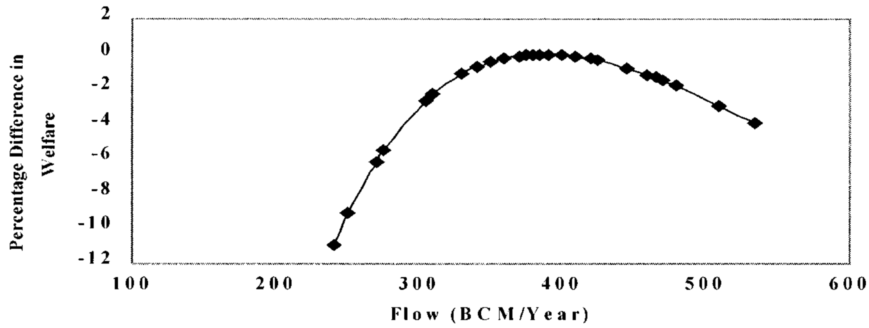


*Figure 5.* Percent difference in welfare as a function of annual flow (simulated).

then accorded to the downstream country (Bangladesh). Using the data on actual flow volumes during the 1949–1985 period, the gap in total basin welfare between the optimal fixed schedule and the flexible schedule was determined on a yearly basis (see Appendix).

The average loss in welfare using the fixed schedule was relatively small, about 1.8%. In fact, total welfare under the fixed schedule was within 1% of the maximum (achieved using the flexible schedule), whenever the total flow volume fell between a point about 0.7 standard deviations below the mean and a point about 0.9 standard deviations above it, which occurred about half the time. Actually, total welfare on the fixed schedule was never too far below the maximum whenever total volume was above average; the gap was only about 4% in a year with volume about 1.7 standard deviations above the mean. Thus this simulation suggests that fixed schedules are not too costly in terms of efficiency when volumes are high (Figure 5).

However, the simulation suggests serious problems whenever total flow volumes are significantly lower than average. Welfare fell by 10% or more whenever total flow was more than 1.5 standard deviations below the mean, an event that occurred about 5% of the time. A gap of 5% between total welfare under the fixed and the flexible schedules occurred whenever the total flow was more than 1.2 standard deviations below the mean, which occurred about 11% of the time. Thus, the simulation suggests that the gain in total welfare from a flexible rather than a fixed schedule is substantial whenever total flow volume is significantly below normal.

## Conclusions

The objective of this paper was to analyze water sharing in river basins in order to determine when one water-sharing schedule is better than another, and which schedules are efficient. Important properties of efficient allocations have been identified that promise to lead to algorithms for calculating efficient water consumption amounts for countries in a water basin. Moreover, the bargaining problem associated with compensation at an efficient allocation has been identified. Finally, the possibility of practical schedules for water allocation that vary according to anticipated flow volumes was assessed. Using annual flow forecasts that are accurate and public, these flexible schedules will be implementable, stable, welfare-maximizing systems. A simple simulation was used to argue that such a flexible system will produce significant gains in total welfare, especially in years with substantially below-normal flow.

Beyond this increase in total welfare, there are other reasons for recommending a system that adjusts riparians' water allocations according to total flow volume. Fixed allocation systems can sometimes be far out of line relative to the supply of water. Particularly in arid regions, where "water is life," river basins are often the scene of international tensions and hostilities. Indeed, water allocation agreements are often negotiated in a very tense atmosphere, in the midst of fears that challenges to water rights will escalate to war. As suggested by Kilgour and Wolinsky (1997), environmental issues are of growing importance to international relations, both as causes for disagreement and as threats.

## Note

1. Country water demand functions have been used in various studies addressing water allocation mechanisms. Examples in the literature include Whittington and Haynes (1985) for Egypt and Sudan, Booker and Young (1991, 1994), and Bennett et al. (1998; as mentioned in Bennett and Howe 1998) for Colorado River Basin States, and Netanyahu et al. (1998) for the water aquifer shared by the Israelis and the Palestinians.

## Appendix: Data for and Results of the Simulation

Parameters used in the demand functions are: $C_{\text{India}}$ = 8 ($10^6$US$); $c_{\text{India}}$ = 0.00125 ($\text{BCM}^{-1}$); $C_{\text{Bangladesh}}$ = 12 ($10^6$US$); $c_{\text{Bangladesh}}$ = 0.005 ($\text{BCM}^{-1}$). Note that $c_i q_i$ is dimensionless. The two illustrative demand functions were designed such that the demand by India is more elastic than that by Bangladesh, to reflect relative water scarcity in Bangladesh.

Optimal flexible allocation to country 1 (India) is given by

$$q_1^*(Q) = 0.8Q - 10\ln(1.5)$$

when the year has flow $Q$, with $q_2^* = Q - q_1^*(Q)$ allocated to country 2 (Bangladesh). Note that the mean annual flow is 387 BCM. The optimal fixed allocation to country 1 is given by $q_F = q_1^*(387) = 245$; under the fixed allocation scheme $q_2 = \max\{Q - 245, 0\}$.

In a year with annual flow volume $Q$, the total basin welfare under optimal flexible allocation is denoted $W^*$, and the total basin welfare under the fixed allocation scheme is denoted $W_F$. The quantity $\Delta$% is the percentage difference between $W_F$ and $W^*$, i.e.

$$\Delta\% = \frac{W_F - W^*}{W^*} \times 100$$

The fact that $W_F \leq W^*$ implies that Δ% is never positive (see Figure 5).

The mean of the $n = 37$ values of Δ% is $-1.702$, with a standard deviation of 2.546. One value of Δ% (≈3%) exceeds 10 in absolute value, and four values (≈11%) exceed 5.

*Table A1.* Annual water flow in the Ganges at Farakka and difference in basin welfare between fixed and flexible allocation schemes.

| Year | Flow (BCM/year) | Δ% | Year | Flow (BCM/year) | Δ% | Year | Flow (BCM/year) | Δ% | Year | Flow (BCM/year) | Δ% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1949 | 400 | −0.044 | | | | | | | | | |
| 1950 | 400 | −0.044 | 1960 | 370 | −0.092 | 1970 | 350 | −0.456 | 1980 | 480 | −1.823 |
| 1951 | 305 | −2.623 | 1961 | 480 | −1.823 | 1971 | 535 | −3.934 | 1981 | 390 | −0.002 |
| 1952 | 340 | −0.76 | 1962 | 425 | −0.358 | 1972 | 240 | −10.954 | 1982 | 370 | −0.092 |
| 1953 | 380 | −0.016 | 1963 | 465 | −1.341 | 1973 | 420 | −0.274 | 1983 | 375 | −0.046 |
| 1954 | 460 | −1.192 | 1964 | 420 | −0.274 | 1974 | 340 | −0.760 | 1984 | 385 | −0.002 |
| 1955 | 535 | −3.934 | 1965 | 270 | −6.123 | 1975 | 465 | −1.341 | 1985 | 445 | −0.787 |
| 1956 | 470 | −1.496 | 1966 | 275 | −5.499 | 1976 | 380 | −0.016 | | | |
| 1957 | 330 | −1.157 | 1967 | 340 | −0.76 | 1977 | 400 | −0.044 | | | |
| 1958 | 410 | −0.136 | 1968 | 310 | −2.27 | 1978 | 510 | −2.920 | | | |
| 1959 | 360 | −0.236 | 1969 | 360 | −0.236 | 1979 | 250 | −9.119 | | | |

Source for flow data: London Economics (1995)

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