PERGAMON

Physics and Chemistry of the Earth 27 (2002) 977–982

PHYSICS and CHEMISTRY of the EARTH

www.elsevier.com/locate/pce

Calculation methods to assess the value of upstream water flows and storage as a function of downstream benefits

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Abstract

With the increasing scarcity of water resources, the issue of water valuation becomes one of the major keys for an efficient utilisation and allocation of water. The renewable and cyclic nature of water implies that analysing the value of water should be integrated with the whole water system rather than considering in situ direct values of water. This paper presents a number of calculation methods to assess the effect of water storage dynamics on the translation of downstream water values into upstream indirect water values. The problem of water reallocation from downstream to upstream is also considered. The analysis shows that storage dynamics play an important role in the opportunity cost of upstream water abstraction. Finally it is shown that water storage in general enhances the overall total value of the water system.

Keywords: Water valuation; Water allocation; Value flow; Opportunity cost; Storage dynamics

1. Introduction

In many parts of the world clean fresh water is increasingly becoming a scarce resource and it should therefore be valued as such. One of the main difficulties in water valuation is strongly linked to the temporal and spatial dimensions of water scarcity. It is obvious that at large scales of time and space there is enough water. Therefore addressing the value of water has to deal with the variability of water availability over time and space. Most research on water valuation is limited to the analysis of water value at the spot where it creates a direct benefit. Indirect benefits of water, values generated downstream, are generally neglected, thus ignoring the integrity of the larger water system.

Water allocation efficiency is one of the main keys to face the growing scarcity of water. In order to meet growing and competing demands water has to be allocated between users such that the overall value of the water system is optimised. It is essential therefore to link the value of water to the water system as a whole. A water particle may generate many benefits at different points in time and space along the path of its movement. Another opportunity the integration of water values with water systems gives is the analysis of upstream–downstream dependencies taking into account the dynamics of the water system.

Chapagain (2000) and Hoekstra et al. (2001) introduced the first version of the "value-flow concept". Their hypothesis is that the full value of a water particle depends on the path it follows within the hydrological cycle and the values generated along this path. Thus, the value of a water particle in a certain place and at a certain point in time is equal to its value in situ plus the value it generates in a later stage (downstream). It is presumed that any value of water can be 'transferred' back to where the water came from. Hence, the value of water flows in the opposite direction of the water itself. The following two diagrams illustrate this.

The following equation describes the water balance of the water flows shown in Fig. 1.

$$Q_{\text{down}} = Q_{\text{up}} - U_{\text{use}} \quad (1)$$

where Q_{up} is the inflow from upstream, Q_{down} is the outflow to downstream and U is the withdrawal for water use. In Fig. 2, the value of water use and the value of the downstream flow are transferred to the source of the water, which is the upstream water flow. This is described by the following equation:

$$V_{\text{up}} = V_{\text{down}} + V_{\text{use}} \quad (2)$$

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1474-7065/02/$ - see front matter
PII: S1474-7065(02)00101-8

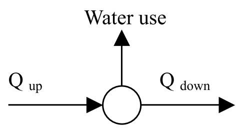

Fig. 1. Water flows at a node.

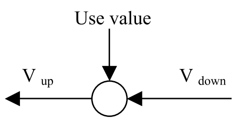

Fig. 2. Value flows at a node.

where V_{up} and V_{down} are the values of upstream and downstream water flows respectively, and V_{use} is the value of water use at the node.

Chapagain (2000) and Hoekstra et al. (2001) elaborated the value-flow concept in a mathematical model and applied it to the Zambezi basin. Their value-calculations were carried out at an annual basis and had a static character. Seyam and Hoekstra (2000) introduced a set of more generic, dynamic equations to deal with the dynamics of the water system within the year, thus allowing the assessment of values on a monthly or even daily basis.

The aim of the current paper is to show how water system dynamics can in various ways affect the value of upstream water. For that purpose a few simple hypothetical cases are considered. The paper is organised as follows. The next section starts with introducing the dynamic value-flow equations and then illustrates how the type of water dynamics can strongly influence the translation of downstream direct water values into upstream indirect water values. Two cases are considered: a system with small water storage capacity and a system with high storage capacity. Section 3 shows how one can calculate the opportunity cost of upstream water abstraction as a function of downstream benefits and water dynamics. Section 4 analyses the added value of a water reservoir as a function of its water storage capacity. The final section gives the conclusions of this study.

2. The effect of storage on the value of upstream water flows

According to Seyam and Hoekstra (2000), in a water system that has a storage component, it is possible to calculate indirect values of upstream water flows by attributing the values generated downstream to the source of water. Let us consider a simple system of one water store S with a number of inflows $Q_{in,i}$ and outflows $Q_{out,j}$ as illustrated in Fig. 3. If an outflow has some value $V_{out,j}$, this value is fully attributed to the stock, which is the source of the outflow. The value of the water stock,

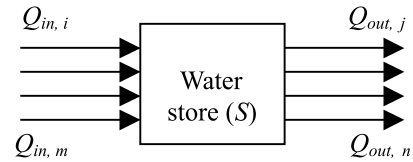

Fig. 3. Water balance components.

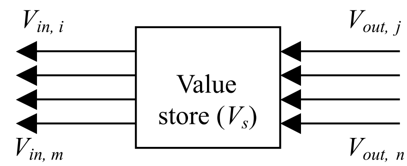

Fig. 4. Value balance components.

V_s, in turn means that a value should be attributed to the water inflows based on their contribution to the stock. Fig. 4 illustrates the flow of water values from downstream to upstream.

The water balance of the water system shown in Fig. 1 can be described by the following equation:

$$\frac{dS}{dt} = \sum_{m}^{i} Q_{in} - \sum_{n}^{j} Q_{out} \tag{3}$$

where S is the water storage in (m^3), Q_{in} and Q_{out} are the water inflow and outflow respectively in (m^3 per month).

The balance of the value of water of the same water system can be written as

$$\frac{dS_v}{dt} = \sum_{n}^{j} V_{out} - \sum_{m}^{i} Q_{in} \tag{4}$$

where S_v is the value of water in the stock, V_{out} and V_{in} are the values of outflow and the inflow respectively in monetary units per month.

The value of a particular inflow $V_{in,i}$ can be calculated based on the value of a unit of water in the stock as in Eq. (5). The assumption here is that the value of a unit of the inflow is equal to the value of a unit of water in the stock. This is similar to the calculation of the load of a substance in the outflow based on the concentration in the reservoir under full mixing.

$$V_{in,i} = \frac{S_v}{S} Q_{in,i} \tag{5}$$

These equations are used here to elaborate the effect of storage on the shape of the calculated value of the water inflow. We consider two cases: a small and a large water reservoir representing a small and a large storage capacity in the water system. Fig. 5 shows the case of a small reservoir. This case can be found in systems with rapid runoff, little delay and a low retention time. Fig. 5a shows that the storage component in the system changes the incoming hydrograph only to a marginal extent (some delay in time and a slightly reduced peak

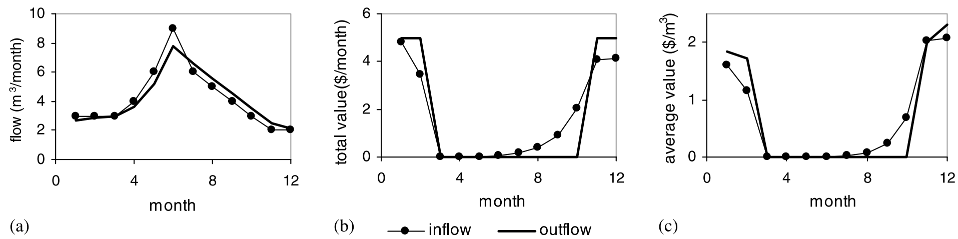

Fig. 5. The translation of an inflow hydrograph into an outflow hydrograph and the translation of an outflow-value curve into an inflow-value curve in the case of a small reservoir. (a) Inflow and outflow hydrographs, (b) total values of water flows, (c) average values of water flows.

discharge). In the example shown we assume that the downstream water flow, the outflow, is used for irrigation (or supplementary irrigation) in the dry season. The total value of the outflow shown in Fig. 5b is given; the total value of the inflow is calculated with the above equations. As can be seen, the shape of the inflow-value curve does not radically differ from the outflow-value curve. The former has just levelled off a bit if compared with the latter. From Fig. 5c one can see the same, but now for the unit value of water ($/m^3).

In a different case, in a water system with a large storage capacity, that is it has a high retention time, the shape of the total value of the inflow in Fig. 6 follows the shape of the water inflow. The case presented in the figures below shows a water system with a large storage capacity as in Fig. 6a where the outflow utilised in the dry period generates a direct value as shown in Fig. 6b. The calculated indirect value of the inflow in Fig. 6b follows the shape of the inflow hydrograph. Due to the high retention time, the unit values of the inflow as shown in Fig. 6c level out over the year.

The effect of the storage capacity on the shape of the indirect value of inflow can be further illustrated by considering the unit value of the water inflow that results from a single direct value of the outflow in a particular month. Fig. 7 shows that for a water system with a small storage capacity the direct value of the outflow translates into a high indirect unit value of the inflow in the few months prior to the month in which the direct value of the outflow is generated. In other words, the direct value of the outflow translates into indirect value within a few months. In the case of a water system with a high storage capacity as in Fig. 8, the same direct value of outflow translates into indirect value of inflow at a lower rate (unit value) and early inflows obtain an indirect value higher than in the case of low storage capacity.

The time period over which a direct value of the outflow in a particular month spreads out as an indirect value of inflow can be termed the memory of the water system. Using this term we can summarize the above elaboration of the value-flow concept in two points. First, the memory of the system depends on the

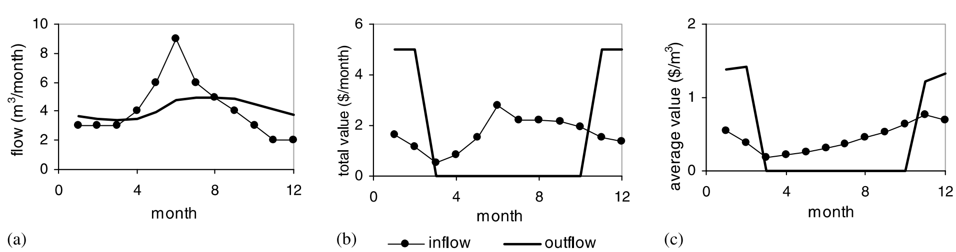

Fig. 6. The translation of an inflow hydrograph into an outflow hydrograph and the translation of an outflow-value curve into an inflow-value curve in the case of a large reservoir. (a) Inflow and outflow hydrographs, (b) total values of water flows, (c) average values of water flows.

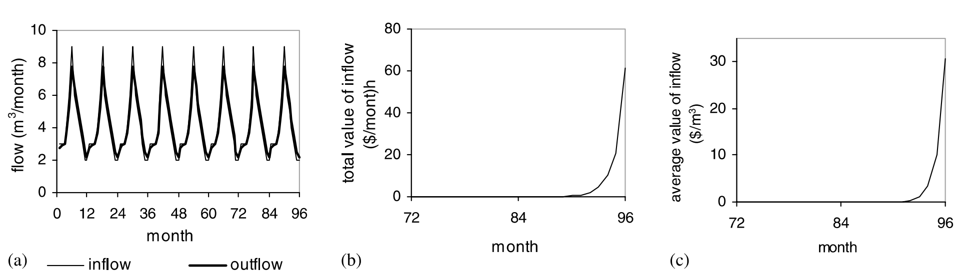

Fig. 7. Transfer of water values in upstream direction in a water system with a small reservoir. (a) Inflow and outflow hydrographs, (b) total values of water flows, (c) average values of water flows.

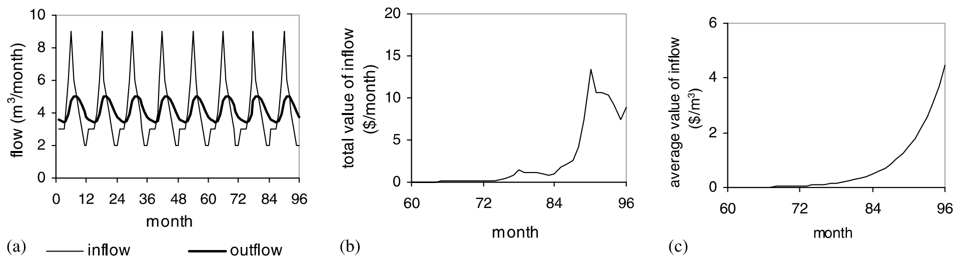

Fig. 8. Transfer of water values in upstream direction in a water system with a large reservoir. (a) Inflow and outflow hydrographs, (b) total values of water flows, (c) average values of water flows.

hydrological properties, namely the retention time in the water storage. Second, in water systems of strong memory, the indirect value of water inflows follows the shape of the inflow hydrograph, while in water systems of weak memory; it follows the shape of the outflow value rather than the inflow hydrograph.

3. The opportunity cost of upstream water abstraction

It is often the case that water in the dry season has a higher direct value than in the wet season. With growing demands for scarce water, water reallocation may be considered such that water is reallocated from an existing water use to a new water use. The concepts of total and average values of inflow presented in the previous section indicate the temporal importance of inflow for the system, but they do not answer the question of reallocation. It is the opportunity cost of water abstraction from the inflow (i.e. the marginal value of inflow) that has to be considered.

In the case water has to be reallocated from downstream users to upstream users, it is not valid to talk about the marginal value of *annual* water inflows without specifying the month in which the marginal unit of inflow is considered. In other words, the marginal value of annual water inflow has a unique magnitude only if the sequence of marginal abstractions from the monthly inflows is specified.

If water is to be abstracted from an individual month, one can look at the opportunity cost of abstracting water from individual months throughout the year to find out the month in which water abstraction has the lowest opportunity cost. This is illustrated in the following example. We consider a simple dynamic water system that has inflow, storage and outflow components, such that the outflow is linearly related to storage by a residence time factor (k). In this example the outflow has a direct value because it is used in a productive activity (e.g. irrigation) during the dry period. The dry period is assumed to last from October to March. In the period January–March, one type of crop is grown, and in the period October–December another crop is grown. For that reason we divide the dry season into two halves

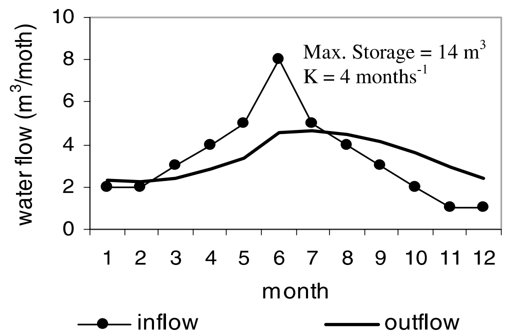

Fig. 9. Inflow and outflow hydrographs before any upstream abstraction.

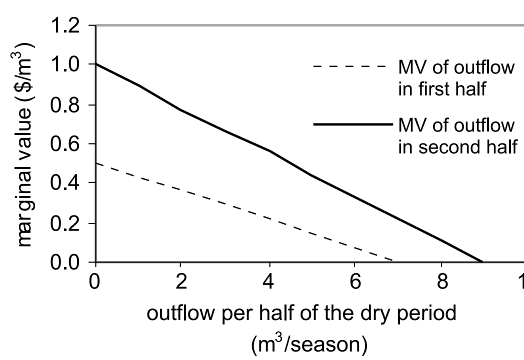

Fig. 10. Assumed marginal value of outflow.

(January–March and October–December). The marginal value of water use downstream is specified such that it is linear but different for the first and second halves of the dry period. The equation of marginal value of outflow in each half of the dry period is specified such that the marginal value decreases against the total outflow in the period. Prior to any upstream water abstraction, the water system generates a total value of 6.25$ per year. Figs. 9 and 10 summarize the basic features of the water system and the water use respectively. [1]

[1] Numbers related to inputs of the illustrative example such as the water inflow are kept small for the sake of maintaining simplicity and they are not meant to be realistic.

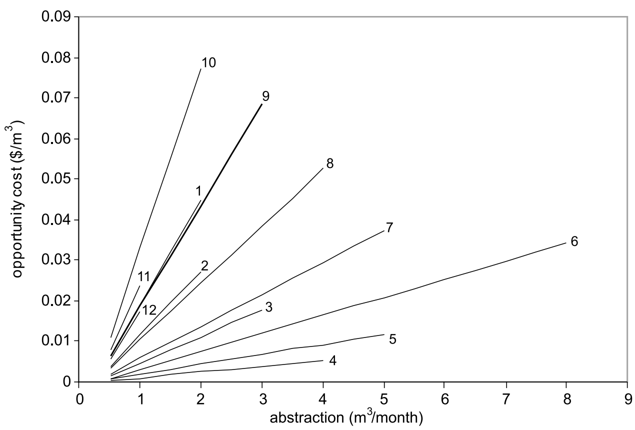

Fig. 11. Marginal opportunity cost of upstream water abstraction calculated for individual.

The marginal opportunity cost of water abstraction from each individual monthly inflow is calculated for the full range of monthly inflow as shown in Fig. 11. It is clear that the marginal opportunity cost of water abstraction follows a distinct line in each month. However the results reflect a static picture of the opportunity cost of water abstraction because the opportunity cost is calculated by exhausting each individual monthly inflow while holding the inflows of the other months constant.

This poses the question "if a certain amount of water has to be abstracted throughout the year, how can we determine the monthly abstractions such that the overall opportunity cost is minimal?". To answer this question it is not enough to look at the opportunity cost of abstractions from individual months; one needs to consider all possible combinations of monthly abstractions.

The optimal marginal opportunity cost of water abstraction specifies the sequence of unit abstractions over months. This can be done in two ways. The first one is to abstract a unit of water in a particular month and calculate the effect on the total value generated downstream, repeating this calculation for all months. Choosing to abstract the first unit from the inflow of the month that has the least opportunity cost, one can move to determine the month in which the second unit is to be abstracted and so on. The second way to do it is to use some optimisation technique such that the annual abstraction from the inflow is broken down into monthly abstractions in an optimal way. The first method has an advantage over the second one in that it gives the optimal monthly distribution of annual abstractions at the full range of the annual abstraction.

For the same illustrative example, Fig. 12 shows the optimal marginal opportunity cost of water abstraction over the full range of the annual inflow. Fig. 13 shows the month from which each incremental unit is abstracted so that the opportunity cost of the total abstraction is optimal. The results show that the first unit

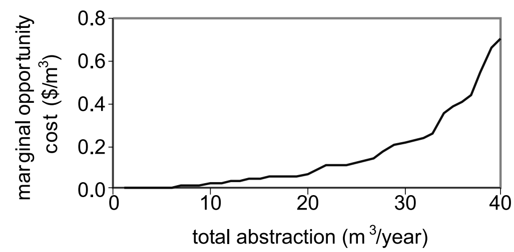

Fig. 12. Marginal opportunity cost of upstream water abstraction calculated by optimising abstractions throughout the year.

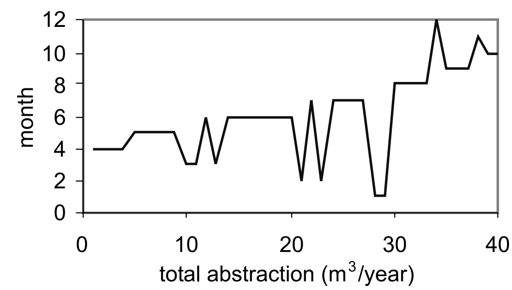

Fig. 13. Months from which incremental units are abstracted.

of abstraction has a zero opportunity cost and it is abstracted from month 4. The marginal opportunity cost increases with the total abstraction and ends up with the last unit of inflow to be abstracted in month 10, the starting month of water use over the year.

4. Reservoir value

Using the same example as presented in the previous section, the reservoir value is calculated as the value gained in the water system due to water storage. Thus the value gained in the system due to having a reservoir of a certain capacity is calculated as the difference in the total value of the system with that reservoir and without it. In this particular example, with a storage capacity of the reservoir of 14 m^3, the total value of the system is 6.25$ per year while removing the reservoir reduces the total value of the system to 4.9$ per year. Therefore the reservoir is attributed an annual value of 1.35$ per year. The total and marginal values of reservoir storage capacity are shown in Figs. 14 and 15 respectively. These figures show that increasing the storage capacity up to about 14 m^3 adds value to the system, whereas beyond this limit there is no gain because the outflows become equal over the months and hence increasing the storage capacity is useless.

Combining such analysis of the gained value of the system due to increasing reservoir capacity with an analysis of marginal cost of reservoir capacity would help decide the optimum reservoir capacity.

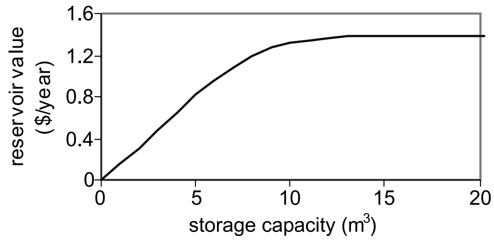

Fig. 14. Value attributed to reservoir at different storage capacities.

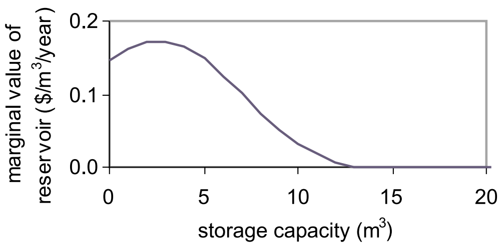

Fig. 15. Marginal value of reservoir storage capacity.

5. Discussion and conclusions

The analysis of upstream water values presented in Section 2 shows that the reservoir size or in other words the retention time of water in storage affects the distribution of upstream water values. While small reservoirs make little difference between the distribution of downstream direct values and upstream indirect values, larger reservoirs make the unit values of inflow level out over the year. Thus, due to the high retention time, water units of peak and low upstream water flows have the same indirect value.

Allocation of scarce water from downstream to upstream users is analysed in this paper by considering the effect of water dynamics on the opportunity cost of upstream water abstraction. The analysis shows that the opportunity cost of water abstraction can be quite different over the year. Therefore, the calculation of the minimum opportunity cost of a certain annual abstraction should account for storage dynamics. The calculated marginal opportunity cost of upstream abstraction shows an increasing trend of the cost of abstracting additional units of water, which reflect a typical cost curve of water supply.

It is shown also that enlarging the size of the reservoir up to a certain level enhances the total value of the system. Beyond that level, enlarging the reservoir does not add to the total value of the system. The calculation of the marginal value of reservoir storage capacity together with a marginal cost curve can be used to assess the net benefits of different storage capacities and hence decide an optimal storage capacity.

References

Chapagain, A.K., 2000. Exploring methods to assess the value of water: a case study on the Zambezi basin. Value of Water Research Report Series no.1, IHE Delft, The Netherlands.

Hoekstra, A.Y., Savenije, H.H.G., Chapagain, A.K., 2001. An integrated approach towards the value of water: a case study of the Zambezi basin. Integrated Assessment 2, 2001.

Seyam, I.M., Hoekstra, A.Y., 2000. The water value-flow concept. Value of Water Research Report Series no. 3, IHE Delft, The Netherlands.