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The water value-flow concept

Value of Water

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Summary

The value of water is a key issue for managing water resources in an efficient, equitable and sustainable way. Efforts to assess the value of water are often lacking a connection to the properties of the natural water system, which makes it difficult to analyse upstream-downstream dependency. In order to account for the cyclic nature of water in the assessment of the value of water, Chapagain (2000) and Hoekstra *et al.* (2000) have introduced the "value-flow concept". This concept aims to provide the missing link between valuation and hydrology. The 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. The full value of a water particle at a certain spot in a certain point in time is supposed to be the sum of its in situ value and all values that will be generated later on along its path. It follows that all values generated by water can ultimately be attributed to the rain. This simple concept implies that there is a direct analogy between the flow of water and the flow of values but there is one big difference. Water values flow backward in time and in a direction opposite to the direction of the water flow. In other words, the value-flow attributes local water values to the upstream water flows within the natural system.

The aim of this paper is to put the value-flow concept in a proper mathematical model that is able to attribute the value of water produced in a certain place and at a certain time to the source of that water. Three models are considered in a progressive manner to arrive at a generic form of the value-flow concept. The first two models were developed and used by Chapagain (2000) and Hoekstra *et al.* (2000). The third model is introduced here in order to properly account for the dynamic nature of the hydrological cycle. It is shown that the third model is the most generic one, able to properly describe the flow of values in a dynamic water system. The parameterisation of the model is based on the hydrological characteristics of the water system. Further analysis of the value-flow concept addresses how return flows generate a multiplier effect for the value of water.

1. Introduction

The principle that water should be managed as an economic good was generally agreed upon at the International Conference on Water and the Environment, held in Dublin in 1992 (ICWE, 1992). Recently, the Ministerial Declaration of the Second World Water Forum, held in The Hague in March 2000, emphasised that water should be managed in a way that reflects its economic, social, environmental and cultural values. Despite the increasing recognition of "water as an economic good" by the international community, it is still debated how one can measure the value of water. Also there is confusion and disagreement about what the idea implies for policy makers, see Briscoe (1996) and Perry *et al*. (1997). In practice, water valuation remains a very illusive subject where a unifying approach is required (Abu-Zeid, 1998). Most efforts have focused on measuring the value of water in certain water using sectors so that only the part of the water cycle closest to the end user is recognised as an economic good.

Next to the conceptual and methodological difficulties encountered in the assessment of the *in-situ* values of water used in a certain time and location, one needs to deal with the cyclic nature of water. A water particle used for a certain purpose will always remain within the water cycle. As hypothesised by Hoekstra *et al*. (2000), the value of a water particle at a certain place and a certain point in time is equal to its value in-situ plus its contribution to downstream benefits generated in later stages. In other words, the full value of a water particle consists of two components: a direct value which stands for the in-situ value and an indirect value which results from translating back downstream values to the source of the water. As opposed to a water flow that goes from upstream to downstream, the process of attributing a value to the source of water can be seen as a reversed process in which water values move in a downstream-upstream direction and backward in time.

The aim of this paper is to introduce a proper mechanism by which direct values of water can be attributed to the source of water. The paper builds on previous work by Chapagain (2000) and Hoekstra *et al*. (2000) who applied simple mathematical equations for the value-flow concept in a case study on the Zambezi basin. The contribution of the current paper is to identify the limitations of the previous work and hence to introduce a more generic mathematical equation for the value-flow concept. The measurement or assessment of direct values is not addressed in this paper. It is assumed here that all direct values are known and the main question addressed is how to calculate the indirect values.

The set-up of the paper is as follows. In the next section, the stationary and dynamic value-flow equations used by Chapagain (2000) and Hoekstra *et al*. (2000) are presented, followed by the main contribution of this paper, that is the introduction of a more generic value-flow equation. In the third section, the value-flow equations are applied to a hypothetical water system to explain where and why the previous value-flow equations fail. The fourth section presents an application of the new value-flow equation to a water system that has return flows which generate the so-called multiplier effect on the value-flow calculation. Finally, in the fifth section we give some conclusions.

2. The value-flow equations

2.1. General

Obviously, water management problems have to do with extreme conditions of water availability rather than with averaged or aggregated conditions. Therefore, water values need to be given in a way that reflects temporal and spatial variations in the value of water. In other words, temporal and spatial resolution of water values should be properly selected to meet the information demand. The full value of water can greatly differ from place to place and from time to time. We address here the question how to assess the *total* full value of a water flow in a certain time step (for instance a month) and in a certain place[1]. To start with, consider a water system with *m* inflows, *n* outflows and a storage component S as shown in Figure 1.

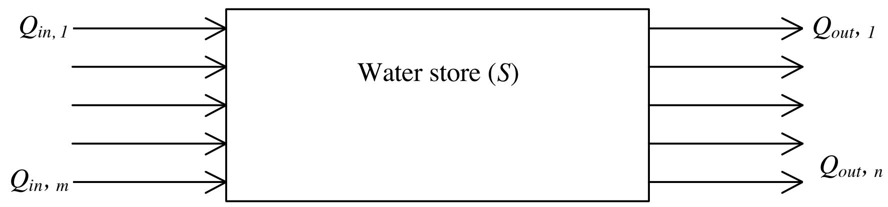

Figure 1 The water balance of water store.

In general, the total full value of a water inflow ($FVQ_{in, i}$) at a given time (t) is given as:

$$FVQ_{in,\,i}(t) = DVQ_{in,\,i}(t) + IVQ_{in,\,i}(t) \tag{1}$$

Where $DVQ_{in, i}$ is the total direct value of the inflow $Q_{in, i}$ and $IVQ_{in, i}$ is the total indirect value of that inflow at the same point in time. As mentioned before, in this paper the direct values are assumed to be known and the main goal is to work out the second term on the right side of the equation, the indirect value. In the water system shown in Figure 1 an inflow has an indirect value if it contributes to the values of the outflows. Thus the contribution of an inflow to an outflow determines the fraction of the outflow value to be attributed to the inflow. In the following, the stationary and dynamic value-flow equations introduced by Chapagain (2000) and Hoekstra *et al*. (2000) are presented followed by a new more generic dynamic value-flow equation.

2.2. Value-flow in a system without delays (Model A)

If the hydrographs of the total inflow and total outflow are identical, that is if water storage does not change over time and the residence time of water in the store is zero, then the indirect value of each inflow can be determined by attributing the outflow values to the inflows according to the contribution of each inflow to the total inflow as follows:

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1 We speak in this paper about the *total* full value, to be distinguished from the *marginal* full value. Where marginal full value refers to the full value of the 'last unit' of a water flow, total full value refers to the full value of the water flow as a whole. The value-flow equations introduced apply for the process of attributing total values of water from downstream to upstream, not for attributing marginal values back along the water flow lines.

$$FVQ_{in,\,i}(t) = DVQ_{in,i}(t) + \sum_{j=1}^{n} FVQ_{out,\,j}(t) \times \frac{Q_{in,i}(t)}{\sum_{i=1}^{m} Q_{in,\,i}(t)} \tag{2}$$

In this particular case the outflow values are immediately translated into indirect values of inflows. This equation is suitable in the case of a large time step (average year), in which the assumption that water stocks do not change will generally hold. However, water management problems concern situations where water stocks vary from year to year and within the year as well. If a water storage changes over time, then the simple attribution of outflow values to inflows as presented in Equation (2) cannot be valid. For instance, if the total inflow is larger than the total outflow within a certain time step, that is part of the inflow is stored, the indirect value of the inflows does not only depend on the value of the outflows in the time step considered, but also on the value of future outflows. If the total inflow however is less than the total outflow, it follows that part of the value of the outflows should be attributed to the inflows of the same time step while the remaining part should be attributed to the inflows of previous time steps. In other words, there should be a mechanism to account for the effect of residence time of water on the attribution of outflow values to inflow values.

2.3. The dynamic model proposed by Chapagain (Model B)

In a dynamic water system with storage, inflow and outflow hydrographs are not necessarily identical. If the net water balance of a certain time step differs from zero, the residence time of water in storage should be accounted for in the calculation of the indirect values. The following equation -proposed by Chapagain (2000)- accounts implicitly for the effect of storage fluctuation:

$$FVQ_{in,\,i}(t) = DVQ_{in,i}(t) + \sum_{j=1}^{n} FVQ_{out,\,j}(t) \times \frac{Q_{in,\,i}(t)}{\sum_{j=1}^{n} Q_{out,\,j}(t)} \tag{3}$$

This equation says that the indirect value of a certain inflow can be determined by the ratio of that inflow to the total outflow. If in a certain time step the net water balance is zero, that is the total inflow equals the total outflow, then this equation reduces to Equation (2). If the total water inflow of a time step is larger than the total water outflow, then the indirect value of the inflow consists of the outflow value in the period considered plus part of the outflow value in a next period. If on the contrary, the total water inflow is smaller than the total water outflow, one cannot attribute the outflow value completely to the inflow of the time step concerned. Part of the outflow value should be attributed to earlier inflows. For a better understanding, Equation (3) can be rearranged as follows:

$$FVQ_{in,\,i}(t) = DVQ_{in,\,i}(t) + \frac{\sum_{j=1}^{m} FVQ_{out,\,j}(t)}{\sum_{j=1}^{m} Q_{out,\,j}(t)} \times Q_{in,\,i}(t) \tag{3a}$$

One now can see that the value of a water inflow in a certain time step is in fact defined as the unit value of outflow in that time step times the quantity of the inflow. This equation holds true only if the unit value of outflow does not change over time.

2.4. A dynamic model based on hydrological properties (Model C)

As the value of an inflow is essentially an attribute of that flow, it is logical to think of the value-flow process in a way that resembles the water flow process. However, contrary to the water flow process, the value-flow process occurs in an upstream direction and backward in time. In general, the water balance of a water store can be written as:

$$\frac{dS(t)}{dt} = \sum_{i=1}^{m} Q_{in,i}(t) - \sum_{j=1}^{n} Q_{out,j}(t) \tag{4}$$

Similarly, the value balance of a water store can be written as:

$$\frac{dFVS(t)}{dt} = \sum_{j=1}^{n} FVQ_{out,j}(t) - \sum_{i=1}^{m} IVQ_{in,i}(t) \tag{5}$$

where *FVS* is the *total* full value of the water stock[2]. Actually this value balance equation can be extended to include a direct value of the stock (*DVS*, expressed as value per unit of time) as in the equation below. Such extension is useful in order to be able to account for direct values of the stock such as recreation value of lakes, wetlands and reservoirs.

$$\frac{dFVS(t)}{dt} = DVS(t) + \sum_{j=1}^{n} FVQ_{out,j}(t) - \sum_{i=1}^{m} IVQ_{in,i}(t) \tag{6}$$

In order to arrive at the correct value-flow equation, it is necessary to first have a water resources equation that can describe the water flow in a reversed direction and then use the hydrological properties of this equation in the value-flow equation. For any water system, the water stock can be related to the water outflow by using a residence time parameter (k_w) as follows:

$$k_w(t) = \frac{S(t)}{\sum_{j=1}^{n} Q_{out,j}(t)} \tag{7}$$

[2] We have to emphasise here again that we speak about the *total* full value, not about the *marginal* full value of the stock. The value balance does not hold if we were to speak about marginal full values.

In the reversed process of the water flow, it is possible to relate the water stock to the water inflow by using another residence time parameter (k_v) as follows:

$$k_v(t) = \frac{S(t)}{\sum_i^m Q_{in,i}(t)} \tag{8}$$

Logically, this residence time (k_v) is the residence time of the value as it flows from downstream to upstream and backward in time. Therefore, the value-flow equation can be written in a form that relates the full value of the stock to the indirect value of the inflow as follows:

$$k_V(t) = \frac{FVS(t)}{\sum_{i=1}^m IVQ_{in,i}(t)} \tag{9}$$

Based on this equation, it is possible now to write the value-flow equation as follows:

$$FVQ_{in,i}(t) = DVQ_{in,i}(t) + \frac{FVS(t)}{k_v(t)} \times \frac{Q_{in,i}(t)}{\sum_i^m Q_{in,i}(t)} \tag{10}$$

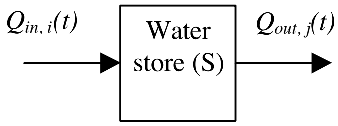
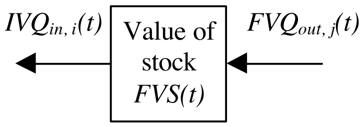
If the equivalent of k_v from Equation (8) is substituted into Equation (10), the value-flow equation reads:

$$FVQ_{in,i}(t) = DVQ_{in,i}(t) + \frac{FVS(t)}{S(t)} \times Q_{in,i}(t) \tag{11}$$

According to this equation, the indirect value of an inflow can be interpreted simply as the product of the water inflow and the unit value of the water in the stock. In other words, the water inflow and the water in the stock have the same unit value. This formulation is different from what Equation (3a) of the previous value-flow model suggests where it was assumed that the unit value of the outflow is equal to the unit value of the inflow.

There is a clear analogy between the water-flow process and the value-flow process, as is shown in Table 1. The key difference is the direction of the flow.

Table 1 Comparison of water-flow and value-flow processes.

Flow process	Balance components	Balance equation	Residence time
Water flow		$\frac{dS(t)}{dt} = \sum_{i=1}^{m} Q_{in,i}(t) - \sum_{j=1}^{n} Q_{out,j}(t)$	$k_w(t) = \frac{S(t)}{\sum_{j=1}^{n} Q_{out,j}(t)}$
Value flow		$\frac{dFVS(t)}{dt} = \sum_{j=1}^{n} FVQ_{out,j}(t) - \sum_{i=1}^{m} IVQ_{in,i}(t)$	$k_v(t) = \frac{S(t)}{\sum_{i=1}^{m} Q_{in,i}(t)}$

3. Testing and evaluation

3.1. General

The value-flow models introduced so far need to be evaluated against transparent criteria. The first criterion is that in a balanced water system in the long run the sum of indirect values of inflows should match the sum of total values of outflows. In other words, if there is no change in the storage of the water system over the period concerned, there should be no change in the storage value. The second criterion is that if the value of an outflow is attributed to an inflow, the model should properly account for the time delay between inflow and outflow.

3.2. Hypothetical example

In order to test the methods introduced here against those criteria, a hypothetical water system of one inflow, one outflow and a single storage is used. The data for the inflow and outflow hydrographs as shown in Figure 2 and Table 2 have been selected so that outflows do not follow any specific water resource equation but they achieve the mass conservation of water over the period considered. Thus the correct value-flow equation should achieve the mass balance of value as well.

Table 2 Water resources data in the hypothetical example.

t month	$Q_{in}(t)$ m^3/month	$Q_{out}(t)$ m^3/month	$S(t)$ m^3	$k_w(t)$ month
1	8	7	50	7.1
2	15	9	51	5.7
3	25	11	57	5.2
4	36	14	71	5.1
5	28	19	93	4.9
6	21	24	102	4.3
7	16	26	99	3.8
8	13	27	89	3.3
9	10	22	75	3.4
10	7	15	63	4.2
11	6	9	55	6.1
12	5	7	52	7.4
Total	190	190		
Average			71	5.0

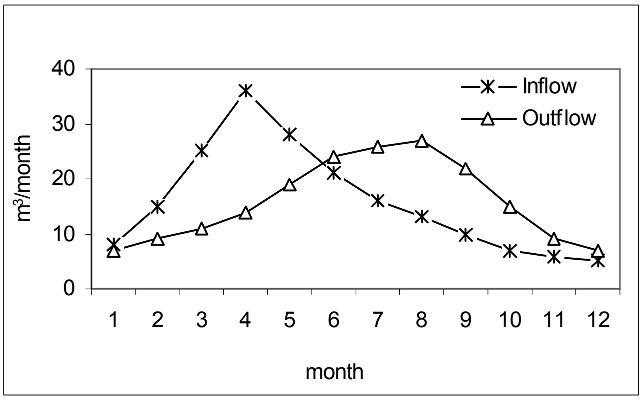


Figure 2 Inflow and outflow hydrographs.

In addition to the water flow data, the full value of the outflow in this hypothetical example is also given (see the inputs in Table 3). We have chosen to express values here in terms of dollars, but we could have used another unit as well. As the purpose of the example is to test the value-flow equations, it is assumed that the direct values of the inflow and the stock are equal to zero. We test the three value-flow models in two cases. In the first case the unit value of outflow (uVQ_{out}) is assumed to be constant over time while it arbitrarily varies in the second case. As will be shown, this distinction makes a difference for the performance of Model B.

Table 3 and Figure 3 show the results obtained from each model under the conditions specified for the first case. Table 4 and Figure 4 show the results for the second case.

Table 3 Inputs and outputs of the value flow calculations, Case 1 (constant unit value of outflow).

	Inputs		Model A		Model B		Model C			
t month	$FVQ_{out}(t)$ \$/month	$uVQ_{out}(t)$ \$/m^3	$FVQ_{in}(t)$ \$/month	$uVQ_{in}(t)$ \$/m^3	$FVQ_{in}(t)$ \$/month	$uVQ_{in}(t)$ \$/m^3	$VS(t)$ \$	$FVQ_{in}(t)$ \$/month	$uVQ_{in}(t)$ \$/m^3	$k_v(t)$ month
1	21	3.0	21	2.6	24	3.0	153	24	3.0	6.4
2	27	3.0	27	1.8	45	3.0	171	45	3.0	3.8
3	33	3.0	33	1.3	75	3.0	213	75	3.0	2.8
4	42	3.0	42	1.2	108	3.0	279	108	3.0	2.6
5	57	3.0	57	2.0	84	3.0	306	84	3.0	3.6
6	72	3.0	72	3.4	63	3.0	297	63	3.0	4.7
7	78	3.0	78	4.9	48	3.0	267	48	3.0	5.6
8	81	3.0	81	6.2	39	3.0	225	39	3.0	5.8
9	66	3.0	66	6.6	30	3.0	189	30	3.0	6.3
10	45	3.0	45	6.4	21	3.0	165	21	3.0	7.9
11	27	3.0	27	4.5	18	3.0	156	18	3.0	8.7
12	21	3.0	21	4.2	15	3.0	150	15	3.0	10.0
Total	570		570		570			570		
Average		3.0		3.8		3.0	214		3.0	5.7

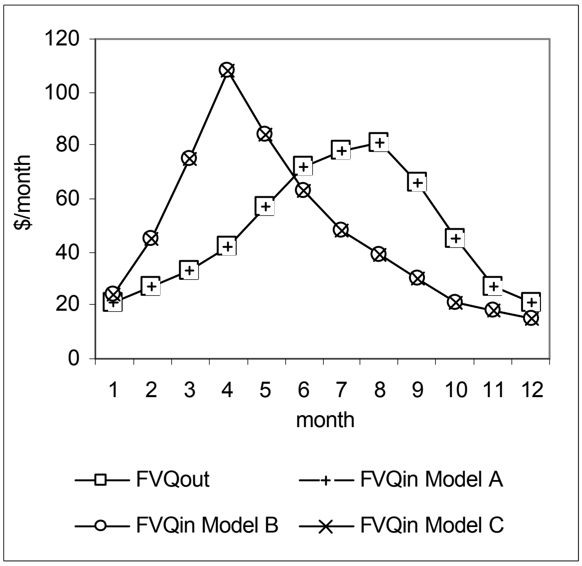


Figure 3a Full values of inflow and outflow, Case 1.

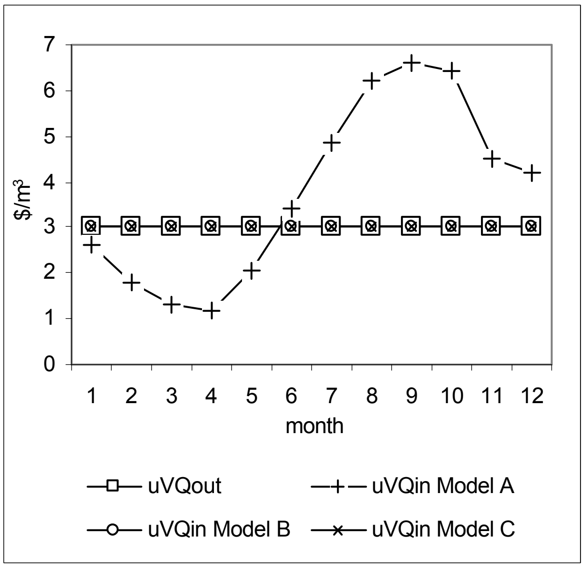


Figure 3b Unit values of inflow and outflow, Case 1.

Table 4 Inputs and outputs of the value flow calculations, Case 2 (variable unit value of outflow).

	Inputs		Model A		Model B		Model C			
t	*FVQ_{out}(t)*	*uVQ_{out}(t)*	*FVQ_{in}(t)*	*uVQ_{in}(t)*	*FVQ_{in}(t)*	*uVQ_{in}(t)*	*VS(t)*	*FVQ_{in}(t)*	*uVQ_{in}(t)*	*k_v(t)*
month	$/month	$/m^3	$/month	$/m^3	$/month	$/m^3	$	$/month	$/m^3	month
1	14	2.0	14	1.8	16	2.0	135	21	2.6	6.4
2	18	2.0	18	1.2	30	2.0	159	42	2.8	3.8
3	22	2.0	22	0.9	50	2.0	211	74	3.0	2.8
4	28	2.0	28	0.8	72	2.0	298	116	3.2	2.6
5	38	2.0	38	1.4	56	2.0	359	99	3.5	3.6
6	72	3.0	72	3.4	63	3.0	364	77	3.7	4.7
7	104	4.0	104	6.5	64	4.0	317	57	3.6	5.6
8	108	4.0	108	8.3	52	4.0	253	44	3.4	5.8
9	88	4.0	88	8.8	40	4.0	196	31	3.1	6.3
10	60	4.0	60	8.6	28	4.0	156	20	2.8	7.9
11	36	4.0	36	6.0	24	4.0	136	16	2.6	8.7
12	21	3.0	21	4.2	15	3.0	128	13	2.6	10.0
Total	609		609		510			609		
Average		3.0		4.3		3.0	226		3.1	5.7

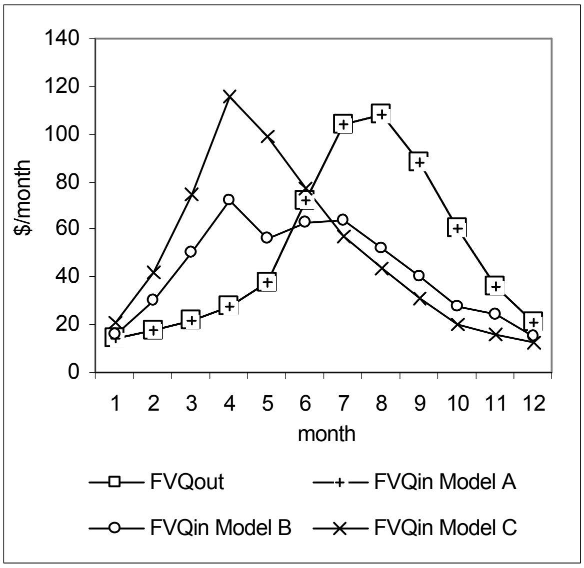


Figure 4a Total values of inflow and outflow, Case 2.

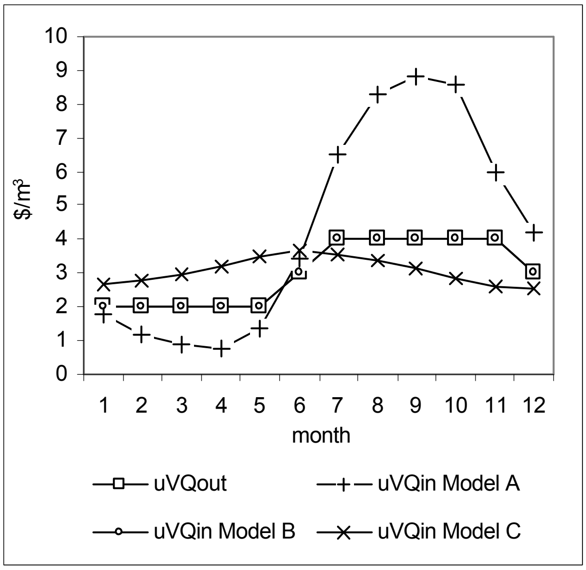


Figure 4b Unit values of inflow and outflow, Case 2.

3.3. Discussion of test results

In the first case of constant unit value of outflow, the results shown in Table 2 and Figure 3a and 3b show that all models conserve the value balance, that is sums of the inflow and outflow values are equal. However Model A obviously does not account for the storage effect. As shown in Figure 3b, the dynamic models B and C result in a unit value of the inflow equal to the unit value of the outflow, which means they correctly account for the storage effect in this case.

In the second case where the unit value of outflow is variable, Model B fails to conserve the value balance because it assumes that the unit values of the inflow and the outflow are equal. This leaves the new model, Model C, presented here as the correct model that performs correctly without any limitations. Table 5 summarises the findings of the test.

Table 5 Summary of test findings.

Model	Case 1 (constant value of unit outflow)		Case 2 (variable unit value of outflow)	
	value balance	res. time properly accounted for	value balance	res. time properly accounted for
A	yes	no	yes	no
B	yes	yes	no	no
C	yes	yes	yes	yes

4. The multiplier effect

In the water cycle, part of a certain outflow may return to the water store, thus generating a multiplier effect on the calculation of indirect values. For example, part of the water withdrawn from groundwater for irrigation use may return to the groundwater store, thus contributing to the irrigation benefits in later stages. Another example is the case where evaporation in a river basin contributes to the rain that falls within the same basin.

In the previous section, it was shown that the dynamic model C is the correct value-flow model. This model is further tested here to show that it accounts for the multiplier effect. The case of return flows from irrigation water is used as shown in Figure 5.

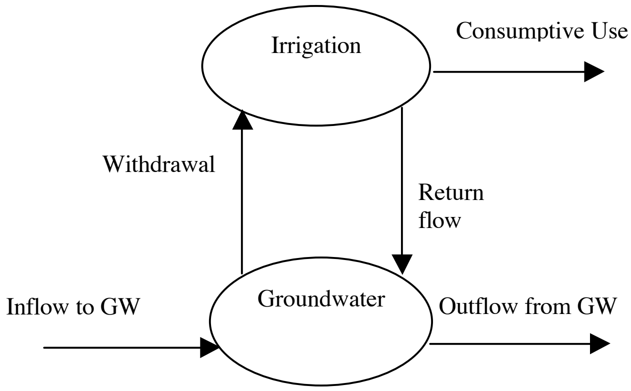


Figure 5 Schematisation of the water flows and stocks of an irrigation system.

In this example water flow data are assumed such that 30% of the withdrawal for irrigation is lost as consumptive use and that the remaining 70% returns to the groundwater store. The example also distinguishes four time steps (four seasons) such that the water balance is conserved over the whole period. The water resources data are given in the Table 6.

Table 6 Water resources data for the irrigation system.

Time step	inflow m^3/season	withdrawals m^3/season	consumptive use m^3/season	return flow m^3/season	outflow m^3/season	GW storage m^3
1	500	600	180	420	400	9920
2	800	700	210	490	500	10010
3	1000	700	210	490	600	10200
4	200	500	150	350	250	10000
Total	2500	2500	750	1750	1750	

Also it is assumed that the consumptive irrigation water use is the only water flow that has a direct value and the water store has no direct value. Thus the purpose of applying the value-flow equation of the Model C is to calculate the indirect values of the water flows in the system which is partially closed. The assumed direct value of the consumptive water use and the resulting indirect values of the other water flows are shown in the Table 7.

Table 7 Input and calculated values of the water flows in the irrigation system.

Time step	Input direct value	Calculated Full Values of water flows				
	FV cons. use $/season	FV withdrawal $/season	FV return flow $/season	FVS_{GW} $	FV inflow to GW $/season	FV outflow from GW $/season
1	1080	1548	468	11054	557	0
2	630	1185	555	11330	905	0
3	420	1001	581	12095	1186	0
4	750	1155	405	11577	232	0
Total	2880	4889	2009		2880	0

The sum of the values over the whole period shows that the full value generated in the system is 2880 $/year. Logically the value of the water inflow into the system is also 2880 $/year. The value of the outflow from the groundwater store is zero because it does not contribute to the water cycle in the system. The value of the withdrawal exceeds the net value generated in the system due to the multiplier effect.

5. Conclusion

The objective of this work was to derive a value-flow model that correctly attributes the value of a water flow to the source of the water under various hydrological conditions. In this report we introduce and test a water value-flow model that it is more generic than the models earlier formulated by Chapagain (2000). The new model is build on the hypothesis that the residence time of value in a water store depends on the hydrological characteristics of the water store. It is shown that the residence time of value is equal to the ratio of water storage to water inflow.

Next to value flows the new model distinguishes value stocks, which allows for the inclusion of direct stock values such as recreational values of surface water bodies. Moreover the new model was applied to a partially closed water system showing that it accounts for the multiplier effect in such a water system.

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