River basin game – Lessons learned (2)

© 2011 Arjen Y. Hoekstra, e-mail: a.y.hoekstra@utwente.nl
Twente Water Centre, University of Twente, Enschede, the Netherlands

The game illustrates the social dynamics that evolve in a river basin where water is scarce, that is where competition over water occurs. You can learn, however, also some basic lessons on hydrology and economics.

1. Understanding hydrology

Many people think that if annual net precipitation in a compartment is X water units, the farmers in that compartment can annually abstract X water units as well. Theoretically, this may be true, but consider what happens to the water storage in the compartment. Visualize a compartment as a full bath tube. In the original equilibrium situation, without farmers, the bath tube receives every year X water units in the form of net precipitation. At the bottom of the bath tube there is a drain, from which on an annual basis X water units leave the bath tube. In this situation, the annual inflow into the bath tube equals the annual outflow, so the water storage (and thus the water level) in the bath tube remains equal. Suppose now that farmers decide to abstract X water units per year from the bath tube. The volume of abstraction equals the volume of net precipitation, so they cancel each other out. There is no net replenishment of the bath tube anymore, because what comes in is taken out. The drain at the bottom of the bath tube remains, however, so that gradually the bath tube will become emptied. The final situation is that we have an empty bath tube, where indeed every year X water units come in through net precipitation, but where at the same time an enormous effort is done to immediately capture every drop of water for irrigation. If farmers indeed succeed to capture every drop of net precipitation, the outflow from the drain of the bath tube will be zero in the long term.

The lesson of the bath tube is that if in a compartment you take out what comes in, this doesn't mean that other things remain equal. In the course of time, the water storage in the compartment will go to zero and the outflow to the downstream compartment will go to zero as well. A declining water storage in a compartment implies that abstracting water will become more expensive per unit of water. It may thus be theoretically possible, from a physical point of view, to abstract from a compartment an amount that is equal to what is replenished through net precipitation, but from a long term economic point of view this is probably not attractive, because costs of abstraction increase at decreasing water storage. And then we have even left out environmental considerations, because declining water levels and reduced water flows will affect ecosystems and societies depending on those flows.

2. Understanding economics – Was there a 'best solution'?

According to basic economic theory, the optimal volume of water abstraction is where the marginal benefit of taking an additional unit of water equals the marginal cost of it. Although this is quite straightforward, it becomes a bit more complex once we realise that the calculation of the 'optimum' abstraction depends on the time horizon chosen. As we will see below, the economic optimum if we optimise over one year is different from the economic optimum if we optimise over the long term. This is caused by the fact that abstractions and benefits made today affect costs in the future. Besides, the optima in the midstream and downstream compartments depend on choices made upstream. In fact, there are several 'best solutions', depending on perspective chosen (one year or long term; one compartment or river basin as a whole).

The economic optimum for the upstream compartment in the first year: A=50

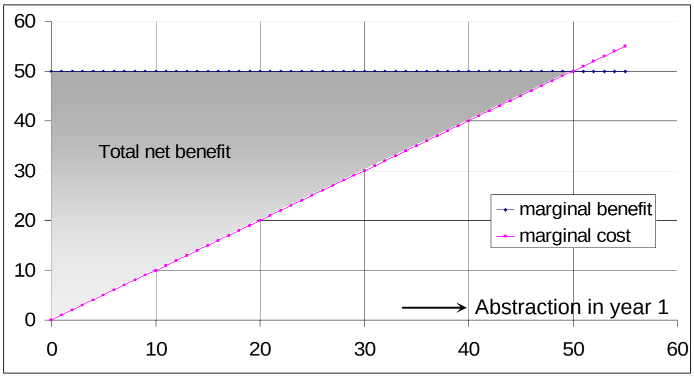
We can consider for instance the best solution for the upstream water users provided that they optimize their group benefit in year 1. The optimal net group benefit for the upstream users in year 1 occurs when the marginal cost of water equals the marginal benefit. The marginal benefit is constant, viz. 50 euro per unit of water. One can easily see that:

Cost of 1st water unit = 1 euro

Cost of 2nd water unit = 2 euro
…
Cost of 50th water unit = 50 euro

So it is best to use 50 units of water (to be shared among the upstream farmers), because above that the benefits are lower than the cost. The net group benefit in euro will be:

$$B_{net} = B - C = 50 \times 50 - (1 + 2 + 3 + ... + 50) = 1225 \text{ euro}$$



For the midstream and downstream compartments, the same optimum can be found for year 1.

The problem with the economic optimum calculated for year 1 is that it depletes water so much that there is little water left to use economically in year 2. An abstraction of 50 units per year is even beyond the annual net precipitation (40 units/year), so it is clearly physically impossible to sustain this volume of annual abstraction in the long term. The physical limit to annual abstraction in the long term is obviously 40 units per year. However, although this is physically possible, it will be economically unfeasible. Already at the end of the first round the water in the upstream compartment would be so much depleted and water abstractions would have become so expensive that abstraction of another 40 units in the second round would result in a net loss instead of a net benefit. The long-term economic optimum must be below the physical maximum.

The economic optimum for the upstream compartment over the long term: A=14

Let us calculate now the long-term economic optimum level of water abstraction for the upstream compartment. The net benefit in a year n is given by:

$$B_{net} = B - C$$

$$\Rightarrow B_{net} = A \times \text{Pr} - A \times \left[\frac{1 + A}{2} + S_i[\text{year 0}] - S_i[\text{year n}] \right] \qquad [1]$$

$$\Rightarrow B_{net} = A \times [\text{Pr} - S_i[\text{year 0}] + S_i[\text{year n}] - 0.5 - 0.5A]$$

A long-term solution requires that the water storage in the compartment is in equilibrium:

$$\frac{dS_i}{dt} = 0$$

$$\Rightarrow P_{net} + Q_{in} - A - Q_{out} = 0 \qquad [2]$$

Applying equation 2 for year n gives:

$$P_{net} + Q_{in} - A - \frac{S_i[\text{year n}]}{k} = 0$$
$$\Rightarrow S_i[\text{year n}] = (P_{net} + Q_{in} - A) \times k \qquad [3]$$

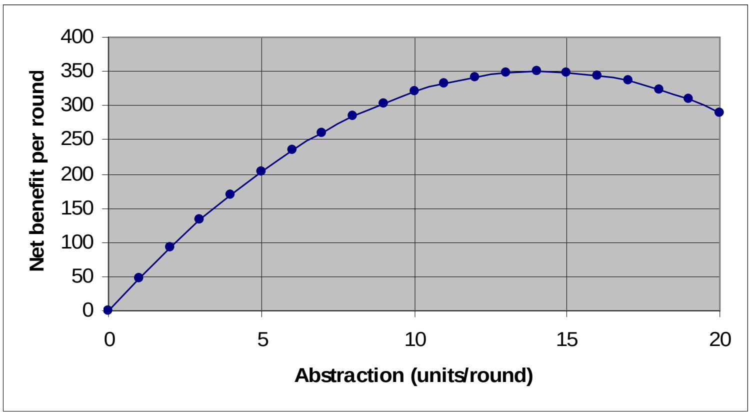
Substitution of S_i[year n] in equation 1 by its equivalent in equation 3 gives:

$$B_{net} = A \times [\Pr - S_i[\text{year 0}] + (P_{net} + Q_{in} - A) \times k - 0.5 - 0.5A]$$
$$\Rightarrow B_{net} = [\Pr - S_i[\text{year 0}] + (P_{net} + Q_{in}) \times k - 0.5] \times A - [0.5 + k] \times A^2 \qquad [4]$$

For the upstream compartment, with Pr=50, S_i[year 0]=50, P_{net}=40, Q_{in}=0 and k=1.25 this becomes:

$$B_{net} = [50 - 50 + (40 + 0) \times 1.25 - 0.5] \times A - [0.5 + 1.25] \times A^2$$
$$\Rightarrow B_{net} = 49.5A - 1.75A^2 \qquad [5]$$

As can be seen from the figure below, the optimum net benefit is obtained is when A=14. In this case the equilibrium water storage in the upstream catchment will be (40-14)×1.25 = 32.5. The annual net benefit in the upstream compartment will be 49.5×14 – 1.75×14^2 = 350 euro (to be shared by the upstream farmers).



The economic optimum for the midstream compartment over the long term: A=9

For the midstream compartment, with Pr=50, S_i[year 0]=75, P_{net}=20 and k=1.25, the long-term optimum depends on what occurs upstream. If there is no water abstraction upstream (Q_{in}=40), the long-term benefit in the midstream compartment is as follows:

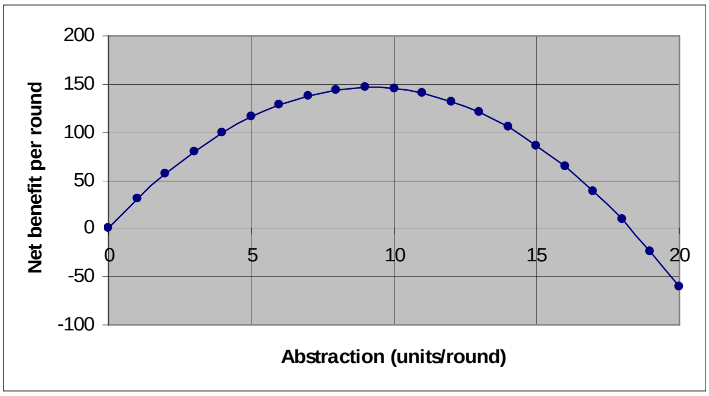
$$B_{net} = [50 - 75 + (20 + 40) \times 1.25 - 0.5] \times A - [0.5 + 1.25] \times A^2$$
$$\Rightarrow B_{net} = 49.5A - 1.75A^2 \qquad [6]$$

As this is the same equation as equation 5, the optimum is again when A=14.

However, when the upstream abstraction is 14 in each round, the outflow from upstream to midstream will in the long term be reduced from the original 40 to (40-14=)26. In this case, the net benefit in the midstream becomes:

$$B_{net} = [50 - 75 + (20 + 26) \times 1.25 - 0.5] \times A - [0.5 + 1.25] \times A^2$$
$$\Rightarrow B_{net} = 32A - 1.75A^2 \qquad [7]$$

The figure below shows that the optimum net benefit is obtained when A=9. In this case the equilibrium water storage in the upstream catchment will be (20+26-9)×1.25 = 46.25. The annual net benefit in the upstream compartment will be 32×9 – 1.75×9^2 = 146.25 euro (to be shared by the upstream farmers).

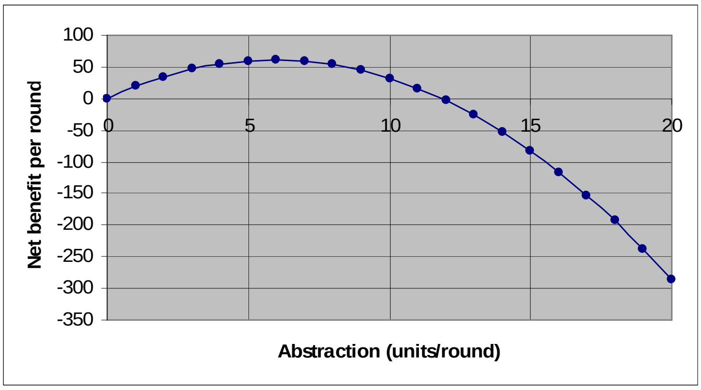


The economic optimum for the downstream compartment over the long term: A=6

For the downstream compartment, with Pr=50, S_i[year 0]=100, P_{net}=20 and k=1.25, the long-term optimum depends on what occurs upstream and midstream. If there is no water abstraction upstream and downstream (Q_{in}=60), the long-term benefit in the downstream compartment is obtained again when A=14. However, when the upstream abstraction is 14 in each round and the midstream abstraction is 9, the outflow from midstream to downstream will in the long term be reduced from the original 60 to (60-14-9=)37. In this case, the net benefit in the midstream becomes:

$$B_{net} = [50 - 100 + (20 + 37) \times 1.25 - 0.5] \times A - [0.5 + 1.25] \times A^2$$
$$\Rightarrow B_{net} = 20.75A - 1.75A^2 \quad [8]$$

The figure below shows that the optimum net benefit is obtained when A=6. In this case the equilibrium water storage in the upstream catchment will be (20+37-6)×1.25 = 63.75. The annual net benefit in the upstream compartment will be 20.75×6 – 1.75×6^2 = 61.50 euro (to be shared by the upstream farmers).



The economic optimum over the long term for the river basin as a whole

The above calculations show that if the farmers optimise their water abstractions within their own compartment, without accounting for the negative effects on the downstream users, the following sustainable but unfair outcome is found:

Upstream: sustainable net benefit is 350 euro/year
Midstream: sustainable net benefit is 146.25 euro/year
Downstream: sustainable net benefit is 61.50 euro/year
} Total: 557.75 euro/year

This total sustainable net benefit in the river basin as a whole can be increased if the farmers from the three separate compartments would cooperate. The computations that are required to calculate the basin optimum become a bit too complex to elaborate here, but a simple example can illustrate the gains of upstream-downstream cooperation.

Suppose that the upstream farmers would abstract 10 water units per year (instead of 14), the midstream farmers also 10 water units per year (instead of 9) and the downstream farmers 9 units per year (instead of 6). In that case we find the following outcome:

Upstream: sustainable net benefit is 320 euro/year Midstream: sustainable net benefit is 195 euro/year Downstream: sustainable net benefit is 79 euro/year	Total: 594 euro/year

The net benefit within the basin would be higher without increasing the total volume of water abstraction, only by sharing differently. Although water shares in the above example are nearly equal, the benefits still differ, because the upstream water use still negatively influences the water availability and therefore the abstraction costs downstream. Benefits could still be more evenly shared by limiting the water quota for the upstream farmers and by allowing the downstream farmers to abstract substantially more water. However, the model shows that benefit sharing at some stage will be at the cost of the net benefit within the basin as a whole.

3. Discussion

A valid question remains of course to which extent the model applied realistically represents real river basin cases. For the purpose of learning, the game focuses on a few variables and processes, leaving out others. Important variables left out are for example other users than farmers and environmental water needs. Water has been made the limiting production factor, while in reality many other scarce production factors play a role, like labour, land and energy. Another simplification is that we do not distinguish between ground- and surface water, by considering just one water storage per compartment.

In the model applied the advantage of the upstream farmers ('first in use') outweighs the advantage of the downstream farmers (who live where all water from the basin collects). If we would choose the model parameters differently, the balance can fall into the other direction. Under current assumptions, for example, upstream water abstractions heavily affect downstream costs of water abstraction. If we would change the cost equation of downstream water use in such a manner that reduced inflow from upstream would impact less on abstraction costs, this would work in favour of the downstream users. We acknowledge that real world cases will differ widely in terms of natural, technological and economic conditions, so that the relative weight of different processes and responses will vary. But we think that our model represents at least two important phenomena that do exist in real cases:

- competition over water within distinguished compartments within the basin, with the threat of free-rider behaviour and overexploitation within each compartment;
- negative effects ('externalities') of upstream water use on downstream users.

Playing the game can give insight in the social dynamics that evolves under such circumstances.