Shortage and surplus of water in the socio-hydrological context

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Abstract Balancing the temporal variability of hydrological conditions in the long- and short-term is often essential for steady socio-economic conditions. However, this equilibrium is very fragile in many cases. Hydrological changes or socio-economic changes may destroy it in a short time. If we extend the bearing capacity of socio-hydrological systems we increase, in many cases, the harmful consequences of failures. Here, two case studies are discussed to illustrate these problems. The limited success at adapting water resources to increasing human requirements without consideration of the natural capacities will be discussed with the example of water use for irrigation in northeastern China. The demand for a new planning approach, which is based on a combination of monitoring, model-based impact assessments and spatial distributed planning, is demonstrated. The problems of water surplus, which becomes evident during floods, are discussed in a second case study. It is shown that flood protection depends strongly on expectations of flood characteristics. The gap between the social requirement for complete flood prevention and the remaining risk of flood damage becomes obvious. An increase of risk-awareness would be more sustainable than promises of flood protection, which are the basis for technical measures to affect floods and (or) to prevent flood damages.

Key words droughts; irrigation; economy; floods; flood protection; risk

INTRODUCTION

Water resources management is based on understanding of the interactions between hydrology and society. Often both components are changing in different ways:

– Sometimes we have coherent relationships, e.g. if the hydrological conditions are goal-oriented and adapted to fulfil the economic expectations of societies. A coherence is also given if social developments affect the hydrological conditions through side-effects, even if these are not intended (e.g. if intensified agriculture results in eutrophication of water bodies by spill-off of nutrients, forcing the development of water transfer systems).
– In many cases, coincidental variations or trends of hydrological and societal conditions overlap and affect the water management conditions in an unforeseeable incoherent way. Such changes have the potential to improve or aggravate the water management conditions from case to case.

Changes of hydrological and socio-economic conditions combine stochastic and deterministic aspects. In many cases we have a co-evolution of hydrological conditions and societies. People use the benefits of favourable local hydrological conditions (e.g. settlements along riversides), expand and adapt them to their needs (e.g. wells using bank filtrate or water transfer), and are affected by self-induced changes of hydrological conditions (e.g. by pollution or water shortages resulting from industrialisation or urbanisation) disturbing the balance between available resources and human needs. There are two different ways to act on changes depending on the existing water management regime: adaptation and transition. According to a definition by Pahl-Wostl *et al*. (2008) a water management regime is the whole complex of technologies, institutions, environmental factors and paradigms that together form a base for the functioning of the management system targeted to fulfil a societal function. Based on this definition these authors specify the differences between adaption and transition as follows:

– Adaptation refers to change within a given regime structure and management paradigm. Structural change in one regime element would still be adaptation if it does not imply any change in other elements.
– Transition refers to structural changes in more than one regime element. Thus a transition involves a change in the management paradigm. Transitions are generally driven by dissatisfaction with the current regime in water management.

Both categories of change demand evident discrepancies between the state of water management conditions and the expectations of societies. In many cases these discrepancies result from creeping developments. Even if such developments become apparent during monitoring, changes of water management practices are often delayed and in many cases are not adequate to the problems. It becomes necessary to analyse the relationships between hydrological conditions and socio-economic developments to recognise problems at an early stage, to avoid critical situations and to ensure sustainable water management.

SIMILARITIES BETWEEN WATER MANAGEMENT ACTIVITIES TO REDUCE THE RISK OF FLOODS AND DROUGHTS

In the following the changes of components of the water management regime will be discussed with the examples of floods and droughts. Shortage and surplus of water are categories that are relevant only in the context of human expectations and are based on human value systems. The social requirements for balancing extreme hydrological conditions result from the uses of water and landscapes. Very often an incomplete knowledge about the hydrological boundary conditions leads to interventions in the hydrological cycle, which have the potential to affect single components locally (e.g. by changes of groundwater recharge) or downstream (e.g. by acceleration of flood waves) in a negative way. In recent decades it has become obvious that, in many cases, enhanced human efforts to prevent harmful consequences of water shortage and water surplus were inefficient or resulted in adverse effects. Local water resources were exhausted by irrigation, and changes of crop-structures caused soil erosion resulting in degradation of landscapes. Newly built reservoirs became sediment traps and caused downstream problems in interactions between surface and groundwater. Flood protection systems failed and caused higher damages than ever before. In many cases such developments originated from a limited knowledge of the natural variability and the cumulative effects of human interventions. Our technical capacities to modify the hydrological conditions seem to be more developed than our capabilities to assess and forecast the results of human impacts and their cumulative effects. A severe drought or a catastrophic flood event can be the beginning of a vicious cycle, starting with effective actions to reduce the harmful consequences of extremes and ending with aggravated water problems, often shifted in space and time from the starting situation (Fig. 1). Examples of such vicious cycles are shown in Fig. 1. At the left side the feedback mechanism of water shortage is demonstrated. It considers the two components of agricultural water resources: "green water", which is stored as soil moisture, forming the basis of rainfed agriculture, and "blue water" in aquifers and rivers, applied for irrigation if the amount of green water is insufficient. The inclusion of "green water" avoids the incorrect notion that only water volumes used for irrigation are needed for food production and provides the water manager with a practical analytical tool for analyses of water flow partitioning (Falkenmark and Rockstrom 2006).

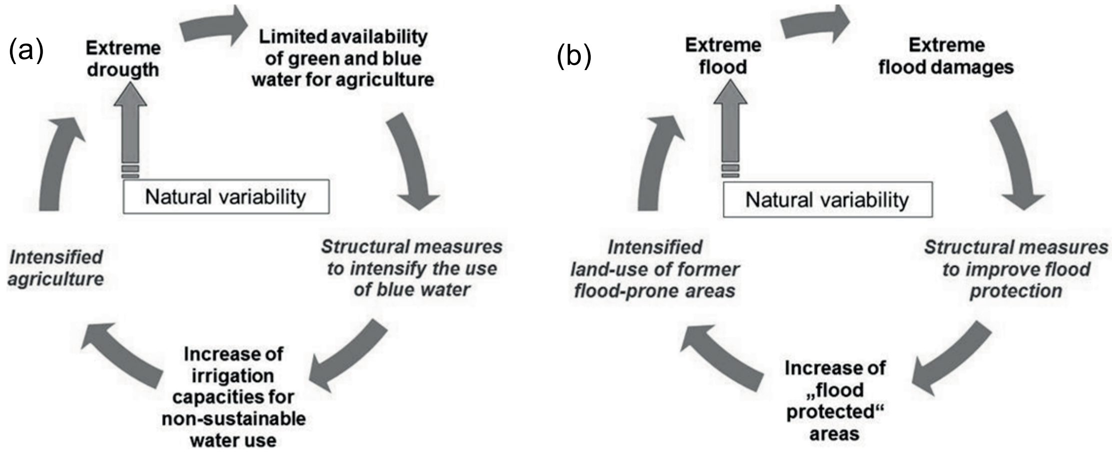

Fig. 1 Different types of feedback mechanisms between hydrological extremes and human interventions: (a) for water shortages, (b) for floods.

There are several factors which cause such developments:

– Often the impact of spatial scale is neglected. Measures are highly effective at the smaller scale but cumulative effects of a multiplicity of these measures have the potential to aggravate the overall conditions.
– In many cases the hydrological variability is underestimated and the limitations of usual design criteria are neglected.
– Side effects that were neglected before have become more important as the human value system is shifting.

To demonstrate these problems, two case studies are discussed here.

Case study 1: Coping with agricultural droughts

In many countries of the world, agriculture is based on a combination of green water and blue water (Falkenmark and Rockstrom 2006). Irrigation ensures a high level of agricultural productivity, fulfilling the needs of socio-economic developments. The demand for irrigation increases temporarily under unfavourable hydrological conditions during an agricultural drought (Tallaksen and Van Lanen 2004). In such a situation, the availability of green water is low but also the recharge of blue water. An increased demand for irrigation has the potential to affect the local water resources in a non-sustainable way if irrigation water is supplied from over-utilized fossil water resources. This feedback has other negative consequences: with a shortage of green water the agricultural productivity declines and the specific price of agricultural products increases. This results in increase of the added value for farmers using blue water. As a result it becomes more economical to enhance the capacity to apply blue water. The irrigation capacities are extended and the non-sustainable use of water is increased further. In this way, the water management problems will be aggravated as the recharge of water resources is reduced permanently. This vicious cycle is shown in Fig. 1 (left).

One country which is severely affected by water shortage is China. With insufficient water resources to meet rising water consumption, over-withdrawal of both surface water and groundwater has become commonplace in northern and eastern China (McCuen 2003). This overexploitation of water resources has led to serious environmental consequences such as rivers drying up, vanishing wetlands, ground subsidence and salinity intrusion. Shandong Peninsula, in the east of the North China Plain, is facing a particularly grim situation with an average total of 357 m^3 fresh water per capita (Fang *et al.* 2010). The study region, the Huangshui River basin in Shandong, is typical for the region where water demands exceed the renewable water resources by about 25% (Sun *et al.* 1998). In the first step of a functional analysis of existing water management conditions, a dynamic water balance was developed, based on observed data and several assumptions about water use and consumption (Fig. 2). This tool could be applied to modify the water balance changing the specific water demand of agriculture as well as rainfall and evapotranspiration.

Analysis of yearly precipitation series from the last 50 years showed a very pronounced downward trend in the study region between 1960 and 1984, with a decrease of almost 8% per year. Over the same period, the crop water demand increased. This demand, which is not measured, was evaluated from agricultural statistics, knowing crop structure and irrigation practices. The reduction of groundwater recharge by intensified agriculture was combined with the most probable amount of blue water derived for irrigation from groundwater and reservoirs. In this way the balance between agricultural water use (including irrigation water demand which is not measured) and the average annual groundwater recharge could be specified by simulations. The irrigation water losses were specified according to the dominant irrigation systems for different crops. Due to the reduced amount of precipitation, the break-even between groundwater recharge and groundwater utilization reduced the limit of sustainable agricultural water demand (including irrigation) from 620 hm^3 /year to 540×10^6 hm^3/year.

To improve the water management conditions, a reduction of agricultural water demand could be reached in different ways: by reduction of agricultural areas (which is not feasible due to social conflicts), by changing the crop structure, by improved irrigation techniques or by combinations of these two measures. Both types of measure were combined within stochastic simulations to estimate the most efficient way of changes. The assumed distribution functions were derived from analyses of statistical data, showing the transformation and adaptation of the agricultural sector in this region during the last decade to changing market conditions. The likelihood of changes was specified from a combination of costs and acceptance measures. In Fig. 3 the exploration of the decision space is shown schematically.

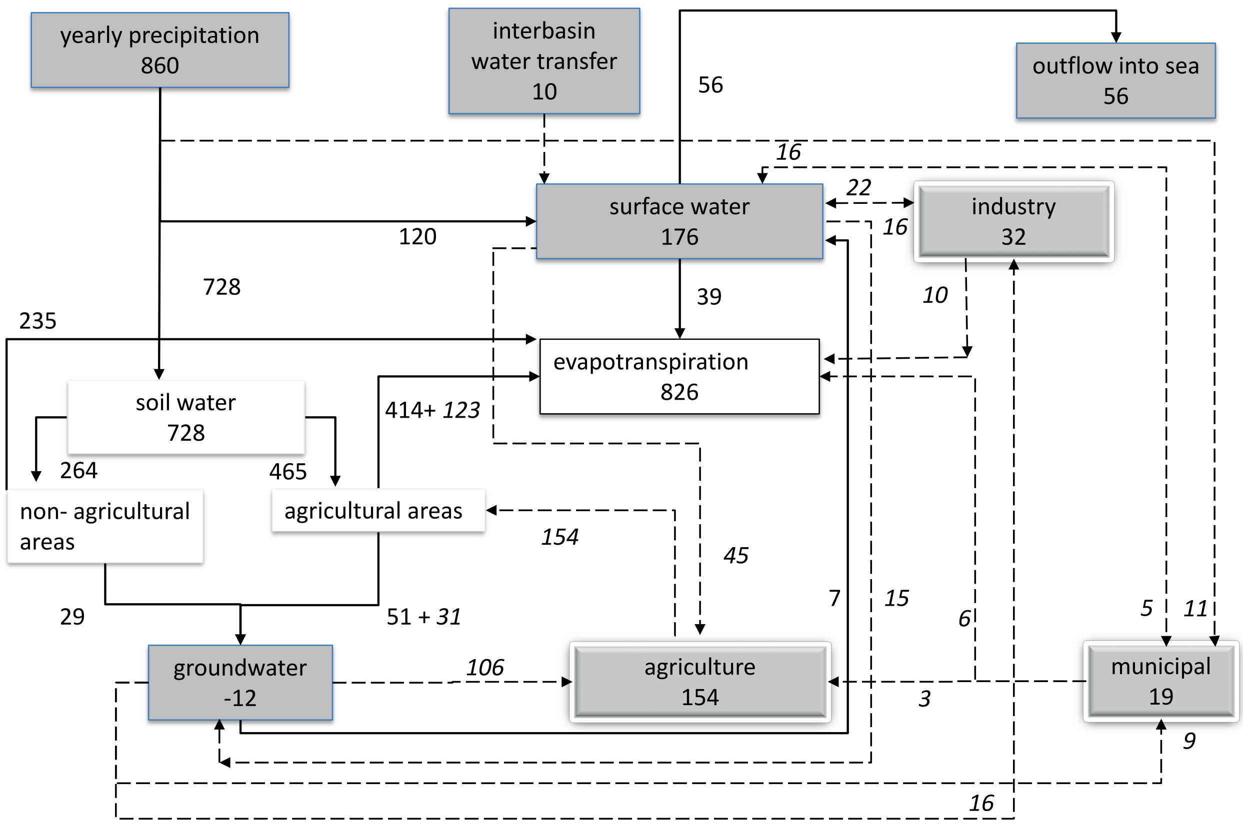

Fig. 2 Dynamic water balance demonstrating the impact of water utilisation (Nijssen 2013). Grey boxes show the available blue water. Dashed lines and italic numbers show human induced water flows, the solid lines the natural flows. All values are given in hm³ per year.

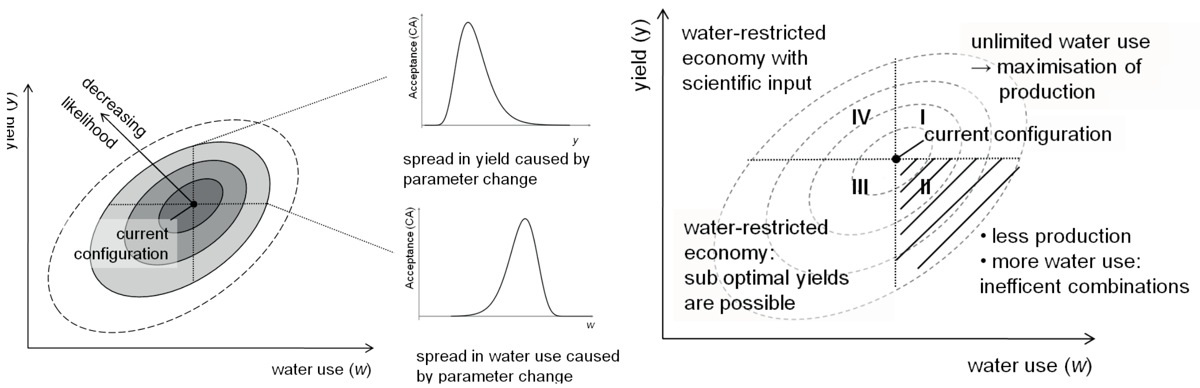

Fig. 3 Strategies to change the agricultural water consumption under consideration of socio-economic effects (Nijssen 2013).

Even if some significant improvements of today's water management could be expected by several combinations of changes of crop and irrigation structures, a continuous reduction of precipitation would result in negative water balance again. Thus a detailed analysis was done in the most endangered part of the basin, where saltwater intrusion would prohibit the utilisation of groundwater in the next decades. It could be shown that a change in crop structure and improved irrigation techniques in combination with a water supply from other parts of the basin ("self-interested solidarity") would stop the on-going trend of salinity intrusion much more effectively than the subsurface sealing wall which was installed in the meantime. The demand for a new planning approach, which is based on a combination of monitoring, model-based impact assessments and spatial distributed planning was demonstrated. However, an institutional framework for control measures does not exist yet. Thus the chances to implement sustainable strategies are low.

Case study 2: Coping with floods by technical retention

Floods result in catastrophic losses all over the world. Between 1950 and 2004, 27% of all economic damages caused by natural disasters resulted from flooding. In the long history of flood protection, the technical means to influence floods and protect flood prone areas were improved more and more. Meanwhile, the economic use of floodplains was intensified. The interactions and feedback loops between hydrological and social processes in flood protection were described in an excellent way by Di Baldassarre *et al.* (2013). The political dilemma of technical flood protection planning consists of the need to "sell" flood protection measures to the public by promising a significant reduction of flood risks and the awareness of engineers that our knowledge about hydrological risk is limited and interactions between operational, technical and hydrological risks could lower the safety limits of technical structures significantly. The safety-oriented approach still dominates in flood design: A design flood defines the limits up to which a flood can be controlled completely by technical measures. A failure of the system is expected only in cases where the design flood is overtopped.

With this paradigm, we promise flood protection up to the limit of a design flood which is often not well defined, especially if we use the classical approach to specify it only with exceedence probabilities of flood peaks. The drawbacks of this approach are obvious: a wide variety of (not considered) hydrological loads could result in failures of the flood protection structures, yet remedial measures are not considered to avoid public discussions about the planned measures.

A more realistic planning approach was realised in a case study in the Unstrut River Basin in Germany (6300 km^2) (Nijssen *et al.* 2009). In this basin a flood protection system exists consisting of several polders and two reservoirs. After the extreme flood in 2003, two different flood planning stages were compared: a reconstruction of two existing but unused polders (measures 1 and 2) and an additional extension of the retention system with four new polders (measures 4 to 6). Instead of a single flood scenario, here multiple scenarios were analysed that differed in the spatial and temporal distribution of runoff. In particular, the relationships between flood peaks and volumes were modified to consider the limitations for flood retention during long floods with large volumes. These scenarios were derived from a copula-based multivariate statistical approach to estimate joint probabilities of flood peaks and volumes. Some results of this study are demonstrated by Fig. 3 where the reductions of flood peak levels at the basin outlet are shown for multiple flood events, specified by the exceedence probabilities of their peaks.

It became obvious that for small floods an increase of retention capacities with newly built polders would be more effective than a reconstruction of existing polders only. However, the differences between the efficiencies with and without new polders became very small for floods with return periods >100 years (Fig. 4). Under unfavourable conditions, both systems would fail and even the frequencies of failures would be very similar. Downstream, the flood situation could be improved by new polders up to a certain level of floods only. Under favourable conditions a flood with a return period of 1000 years (here the return periods were specified by the probabilities of flood peaks at the basin outlet without flood retention) could be retained significantly, but a 50-year flood would not be affected under unfavourable conditions. Multivariate statistics are useful to specify complex flood scenarios in a more realistic way than by probabilities of flood peaks. This study demonstrated the need to consider hydrological uncertainty and variability in a complex way to demonstrate the limitations of water management under unfavourable conditions.

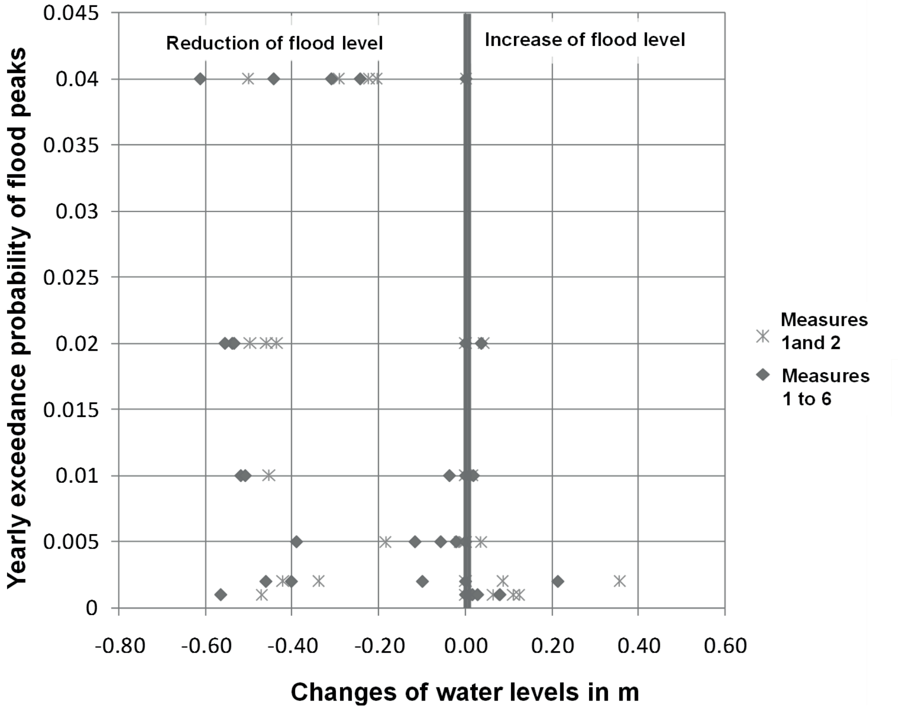

Fig. 4 Changes of flood levels at the basin outlet by two different combinations of measures. For measures 1 and 2 the existing polders are reconstructed; the combined measures 1 to 6 involve four new polders. It can be seen that additional polders reduce the flood peaks up to a 50 years flood, but would not result in significant improvements of flood protection for higher return periods.

CONCLUSION

The main conclusion from the two examples given above is the need to accept the limitations of water management under hydrological and socio-economic changes. In the Chinese case study, the abilities to use groundwater for irrigation increased with socio-economic changes. The farmers earned a higher income which was applied to intensify their irrigation systems. The amount of pumped groundwater increased and exceeded recharge. There are options to handle the problems of saltwater intrusion; however the deficits of the existing institutional framework to control water users cannot be compensated by technical measures. In the second case study, straightforward planning for a technical flood-retention system was discussed, where the uncertainty of specifications of critical hydrological loads were considered. The limits of technical flood retention could be shown for both planned alternatives. The differences between the results of these alternatives are not significant for more extreme floods. An extension of the retention system would improve the flood protection up to a return period of 50 years, but could fail under unfavourable hydrological conditions in a similar way to the existing system. The illusion of complete protection against floods could not realized by any combination of measures. However, the drawbacks of existing design criteria became evident and the need for a much more differentiated consideration of hydrological characteristics could be demonstrated.

Both examples show that hydrology has to be interlinked with the social requirements for information about water. This can only be done interactively: analysing the approach, how hydrological information is used and what developments within the societies affect the hydrological conditions in future.

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