GETTING BACK TO BASICS: THE HYDROLOGICAL CYCLE REVISITED FROM A VIRTUAL WATER PERSPECTIVE

Anthony Turton[i]
Anton Earle[ii]
AWIRU[iii]

Introduction

One of the cornerstones of Water Resource Management is the Hydrological Cycle. The trend towards IWRM suggests that we should revisit the paradigms that serve to guide our thinking of the way that management structures are designed. This has particular relevance for developing countries where readily available water resources have already been allocated to various productive uses, and where water scarcity can impact negatively on the economic growth potential of the state. The core management issue is the propensity towards complexity (Falkenmark & Lundqvist, 1995:189) and the need to rethink and refine the fundamental concepts. The concept of the hydrological cycle needs to be expanded to include an understanding of the various factors involved in IWRM today. These include social, economic and environmental aspects. Four distinct components to the hydrological cycle can be identified:

1. The *Natural Domain* consists of precipitation and other climatological flows.
2. The *Engineering Domain* consists primarily of water that has been made available through human technical ingenuity (consisting largely of "blue water").
3. The *Institutional Domain* in which WDM and other allocative measures are taken in order to improve the efficiency of water use.
4. The *Trade Domain* in which national-level water deficits can be ameliorated by virtual water trade (Allan, 2000), which mobilizes "green water".

There are diverse linkages between all four of the above components, forming a complex system of cycles within cycles. It is the institutional domain where linkages between the other three domains are determined. Water can be moved from the natural domain of one region through either the engineering or the trade domain and rejoin the natural domain in another region. This paper consequently seeks to revisit the hydrological cycle in order to contextualize it in the virtual water discourse in order that we can challenge the prevailing IWRM paradigm and push the envelope of new knowledge further.

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[i] Head of the African Water Issues Research Unit (AWIRU) and present holder of the GIBB-SERA Chair in IWRM.
[ii] Deputy Head of AWIRU and the Southern African Coordinator of the Universities Partnership on Transboundary Waters.
[iii] Part of the Centre for International Political Studies (CIPS), University of Pretoria, Pretoria, 0002, South Africa. E-mail: antonearle@mweb.co.za & aturton@csir.co.za
Telephone: +27-12-420-4486; +27-(0)82-450-7967; +27-11-665-3645

Beyond Portable Water

The first region in the world to run into water deficit was the Middle East North Africa (MENA) (Allan, 2000), with the Southern Africa Development Community (SADC) region set to follow this trend. This means that there is a pressing need to develop new ideas for the management of water resources if local water scarcities are not to become a limiting factor to the economic development potential of the SADC region. Pioneering work by Falkenmark (1994; 1997) has shown that the conventional hydrological cycle can be broken down into two distinct fractions. The "blue water" fraction is the water that is used for socio-economic activities, whereas "green water" is used for biomass production. Similar pioneering work by Allan (2000) has shown that virtual water trade is a powerful yet politically silent way of balancing local water deficit. Work by Turton (2002) has shown that issues of scale and range are central to an understanding of hydropolitics, of which water resource management is but a component. The shift in transboundary water resources management has been away from exclusive water sharing and towards benefit sharing, units of water being just one of many benefits a water resource may offer.

Conventional thinking on the hydrological cycle as well as water resources management generally has given prominence to "portable water". Water which can be pumped, stored, packaged or sold, the blue water referred to by Falkenmark. However, when it comes to food production it is not the portable or blue water which is most important. Close to 60 percent of all grains are produced under rainfed conditions, accounting for about 70 percent of grain production area worldwide. In developed countries, where the majority of the world's grain is produced, rainfed agriculture accounts for about 80 percent of grain area (Rosegrant et al, 2002). Rainfed agriculture relies on soil water, the moisture trapped between soil particles. It is largely ignored by water managers and receives little attention in debates over privatisation of water resources as it cannot be stored or sold.

Water for food production is the largest consumptive use of water, with roughly 1,300 m3/p/y needed to produce the food for a balanced diet (Rockström, 2002). This equates to 5,400 km3/y of water used globally to produce crops. Of this global amount 695 km3/y is traded between countries as food-crop related virtual water (Hoekstra & Hung, 2002). It is this trade in water-intensive crops which makes green water portable and able to be used to compensate for a lack of water resources in other parts of the world. The trade in virtual water between countries is many times greater than that of "real" water. Pipelines, canals, tankers and other water transfer schemes are costly and only able to transport quantities of limited use to an economy. In contrast, a massive and relatively frictionless system of trading virtual water through the world's grain markets is already in place. The great advantage enjoyed by trading in grains is the thousand-fold gearing up in volumes of water saved in relation to grain transported. The trade domain of the hydrological cycle plays an important role in enabling the other two human-constructed domains, while ameliorating shortfalls in the natural domain.

Hydrological Sub-cycles

The Natural Domain consists of the flows of water vapour through the global weather systems. These flows are typically included in the standard model of hydrological cycle. As such it functions at the highest level of scale straddling continents and ecosystems. This embraces aspects such as global climate change, natural climatic variability, ecological water, precipitation, natural flows and fluctuations in those flows. Very little control is possible over these elements. The principle drivers are precipitation, infiltration, evapo-transpiration, vapour transfer and runoff (see Figure 1).

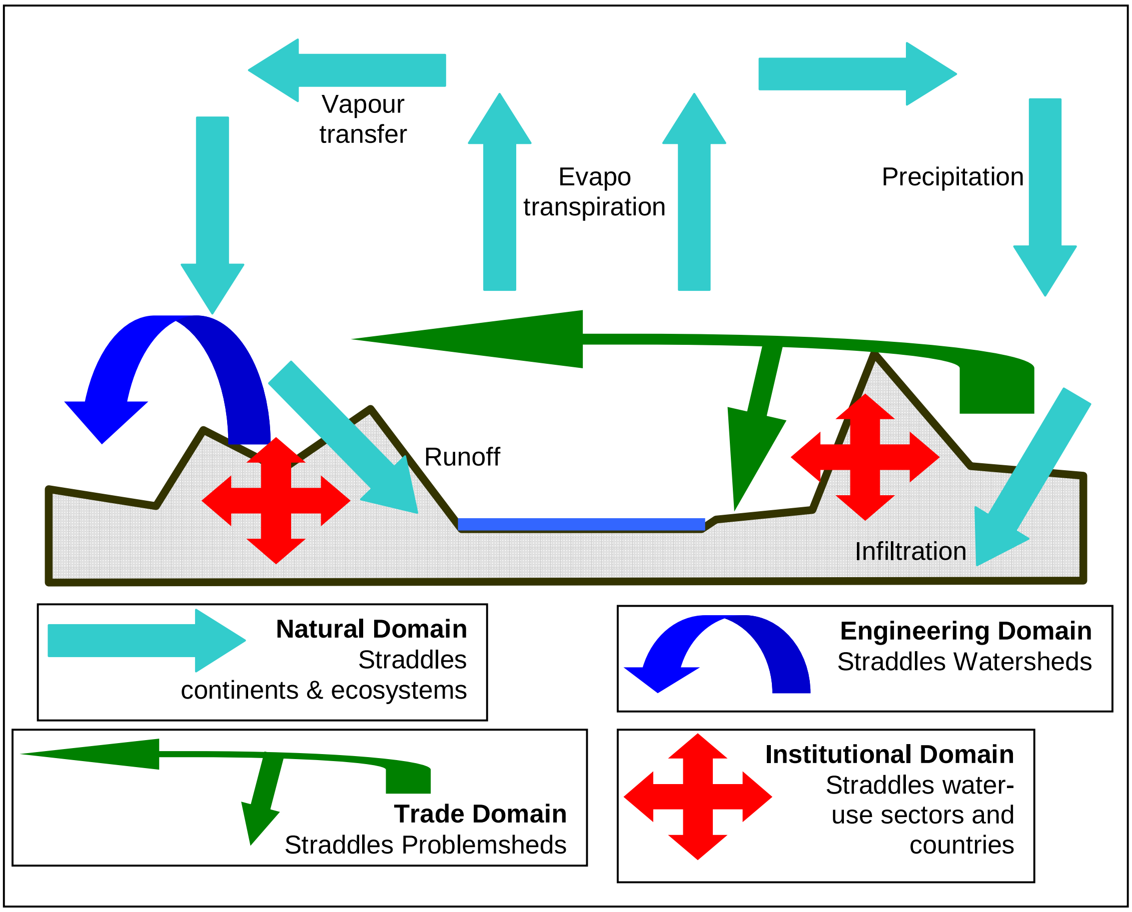

Figure 1: The various domains of the hydrological cycle operate at different scales – from the basin to the global level.

The Engineering Domain is technical ingenuity dominant (Homer-Dixon, 2000) and focuses on the mobilization of the blue water fraction of the hydrological cycle to compensate for local water scarcity. As such it functions at the lowest level of scale. It consists of aspects such as Inter-Basin Transfer (IBT), desalination, the recycling of effluent and aquifer development. The important aspect to note is that the level of scale is limited to the river basin, where at best it can straddle a given watershed. This is the human reaction to water scarcity and variability and underpins water management in places such as the western USA over the past century, southern Africa, India and China. Typically such schemes have various drawbacks associated with them – they have limited capacity, are costly to construct and to operate, have unpredictable environmental consequences and exposes recipient states to insecurity in their water supply.

The Trade Domain focuses on the green water fraction of the hydrological cycle, in particular mobilizing water from regions of relative water abundance in order to balance localized water deficits as they occur. As such it functions at the third level of scale, straddling problemsheds, with the main vehicle of delivery being trade in water rich products. A central issue here is the relative advantage of specific productive modes, with globalization dynamics playing a major role. Factors such as agricultural subsidies, trade barriers and consumption patterns influence the flows of virtual water. The major impact of this domain is that it allows local water supplies to be used in the most efficient application – *more jobs per drop*. Unlike water transfer schemes the supplier basin or state is not locked into an agreement with any one recipient and is free to gain maximum income from the product exported. For the recipient basin or state there is not the insecurity which accompanies being dependant on another state for water supplies. Political instability in the donor state won't necessarily affect the provision of virtual water in the recipient state as there are so many other suppliers on the world market. The major disadvantage, specifically for developing nations, is that it places a limit on their economic development options. Frequently the local economy is not sufficiently diversified to make use of the local water saved in more efficient industries such as industrial manufacturing.

The Institutional Domain is social ingenuity dominant (Homer-Dixon, 2000) and focuses on issues relating to the allocation of water, particularly under conditions of basin closure where all available water has already been allocated to productive activities (Seckler, 1996). As such it functions at the second level of scale, straddling watersheds and international borders where appropriate. Its main focus is the river basin however, where the primary vehicle of delivery in terms of water resource management is policy centred on allocative efficiency and conflict attenuation. It is dependant on being able to make use of the benefits offered by the trade and engineering domains. The importation of virtual water frees local supplies, which can be used in more efficient activities.

It is in the institutional domain where water allocation decisions are made and enables a region to make use of either water transfers or virtual water imports. The local water supplies saved will then re-enter the natural domain as a sub-cycle of the hydrological cycle, either as runoff after a productive use or as ecosystem replenishment (see Figure 2). The last point is important in the conservation of natural water resources such as wetlands and deltas. For example in the management of the Okavango Delta, a Ramsar site in Botswana, a conscious choice has been made to leave water in the ecosystem allowing it to perform important natural processes. Instead of drawing water from the delta to irrigate crops food is imported using income derived from tourism in the delta. The water in the delta either joins the natural domain of the hydrological cycle through evapo-transpiration or through infiltration, leading to evaporation later on.

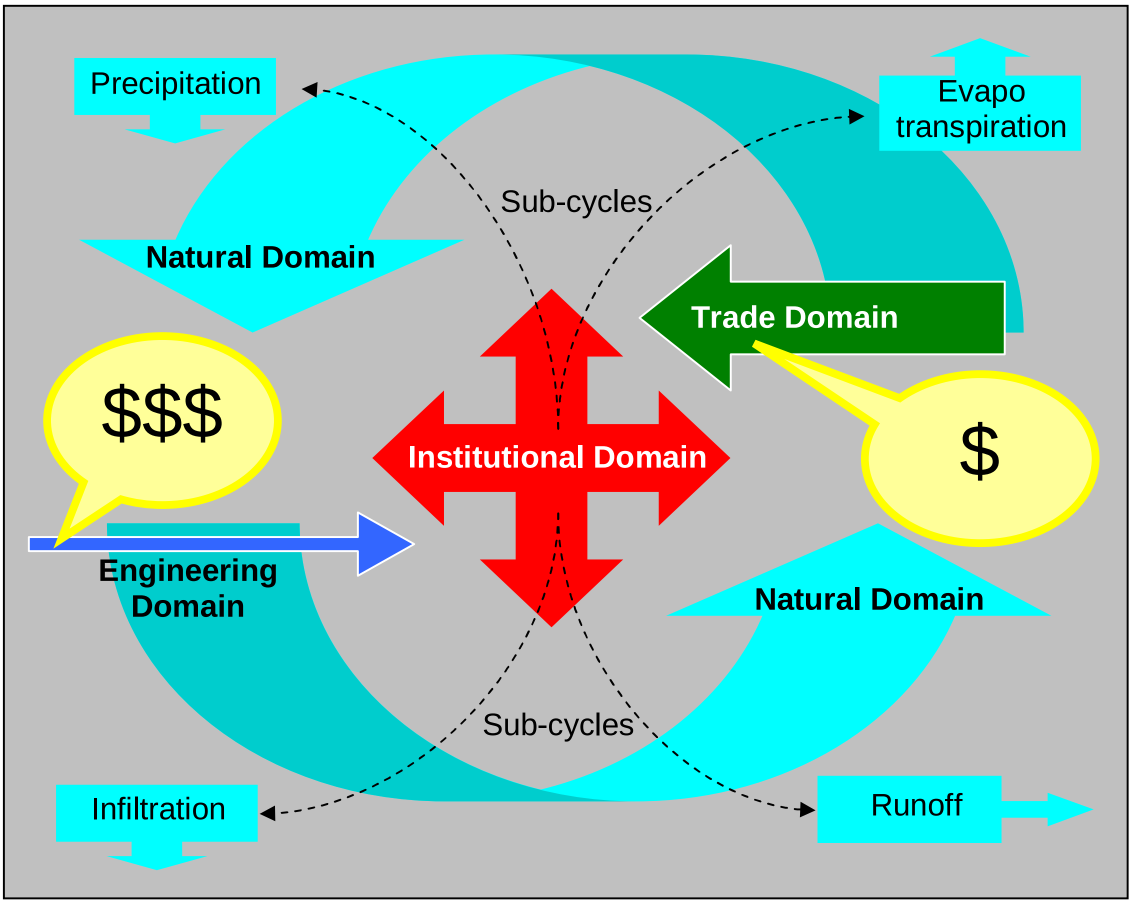

Figure 2: Interaction between the 4 domains of the hydrological cycle

Interaction Among Domains

For the hydrological cycle to maintain its relevance to IWRM it needs to evolve and adapt to the new forces operating within it. The anthropogenic domains had little influence on the natural cycle prior to the agricultural revolution 12,000 years ago. Prior to the origination of large-scale crop cultivation, irrigation and trade in produce, water management activities were minimal. The natural domain of the hydrological cycle operated without interference from humans. With the rise of irrigated agriculture in Mesopotamia water was manipulated, stored and transported moving it away from the natural and into the engineering domain. Over the long-run this control of water resulted in large-scale salination of the soils in the region, as water left the engineering & institutional domain and reverted to the natural domain through evapo-transpiration, leaving salts behind in the process. Over time, as over areas and cultures started practising large-scale irrigation and crop cultivation water would leave the natural domain of the cycle and, through trade, move into the institutional domain. An early example of this virtual water trade is the Roman importation of wheat from Egypt (Allan, 2000).

The industrial revolution and the development of large-scale intensive grain farming in the American mid-west saw a massive increase in the volumes of water moved through the different domains of the hydrological cycle. As comparative advantages between regions of the world became greater with higher levels of specialisation so did the trade in virtual water increase. Areas which had previously produced their own staple foods started focussing on other, higher value, activities and importing their food needs from regions suited to grain production. Also during this period areas of the American west were settled, with water transfer schemes constructed to supply water to cities such as Los Angeles as well as to develop irrigated agriculture in the region.

During this time of the hydraulic mission the emphasis was placed on moving water out of the natural domain using large-scale engineering schemes. Water was stored in ever greater volumes and transported over ever greater distances. In various parts of the world the negative environmental consequences of such large-scale water transfers started making themselves felt.

Water can be stored and moved using engineering skills, but it must eventually always revert to the natural domain of the hydrological cycle. The water moved is subject to the sub-cycles of infiltration, evaporation & runoff. The long term pattern has been for demand for water to continually outstrip supply, as the portion of the newly engineered water reverting to the natural domain of the hydrological cycle stays the same. The institutional response to this in many parts of the world over the past two decades has been to utilise water more effectively once in the institutional domain – incorporating increasing levels of complexity (see textbox alongside). Instead of using social resources to construct ever greater water transfer schemes the trend has been to devote social resources to reduce the quantities of water transferred back into the natural domain through infiltration, evaporation and runoff. Productive efficiency measures such as waste water treatment, efficient irrigation systems, lowering evapo-transpiration losses by growing plants in PVC tunnels and covered or underground storage reservoirs all aim to maximise the amount of water kept in the institutional domain. But there are limits to what can be gained by productive efficiency measures alone. For an economy to continue to develop it is necessary to increase the level of complexity in the institutional domain. Allocative efficiency measures, frequently driven by charging market related prices for water, shift water supplies to the most productive use. The mechanism for achieving this shift is the

Parallels in complexity science

The emerging water management enterprise of the future can be described as a complex adaptive system. In complexity science, natural adaptive systems fluctuate among three states, namely a static state, a chaotic state and a zone of creativity in-between, called the edge of chaos. Computer models show that complex adaptive systems often evolve themselves to the edge of chaos state, where the emergent response is most creative. From this state the emergent order will be richer, more creative and adaptable if there is a diversity of agents in the system; agents with different characteristics and different behaviour.

Depending on the prevailing environment, so too, will an institution fluctuate among the three states. A command-and-control style of management tends to keep organisations close to the static state, because it minimises interactions among its components. This, in turn, impedes the emergence of creativity from leaders as well as operational people. This management style will clearly not suffice in times of transformational change (Lewin and Regine, 1999).

freeing up of vast quantities of local water supplies, both natural as well as engineered, by importing virtual water. Although not directly contributing to water supplies in the way that engineered water does virtual water is a powerful tool in preventing water from leaving the institutional domain into the natural domain.

A good example of the potential effect of virtual water imports on local water supplies can be found in southern Africa. Among the continentous SADC states there is a large variation in water resources available. Generally the southernmost states such as South Africa, Botswana and Namibia are much drier than the states to the north – Angola, DRC and Zambia. For this reason there has been mention of plans in South Africa to one day tap the waters of the Zambezi and, eventually, the Congo rivers via a series of water transfer schemes. Although no formal plans or cost-benefit analyses have been carried out it is possible to estimate operational and capital expenses extrapolated from the Lesotho Highlands Water Project (LHWP) between Lesotho and South Africa. Based on these figures the cost of importing (transferring) seven million km3/y would be about US$ 1,500 annually. This represents a low estimate, as the LHWP is gravity-fed so does not have high O&M costs. Water from both the Congo as well as the Zambezi would have to be pumped over a kilometre in altitude to reach South Africa. Whereas, if the dry countries of the region import 50 percent of their grain requirements (compared to the present average of 20 percent reliance on imports), it would free up about 7 km3/y at a cost of US$ 840 million (based on a CIF price of $ 120/tonne). This 7 km3 saved annually can be used in more productive sectors of the economy forestalling the need to embark on engineering solutions and keeping a greater quantity of water within the institutional domain and allowing less to be "lost" to the natural domain.

Conclusion

For a shift towards a greater reliance on the trade rather than the engineering domain of the hydrological cycle to take place there has to be continued evolution of the institutional domain. Where the hydraulic mission phase was highly planned, centralised and controlled the "reflexive phase" will be increasingly chaotic, unplanned and market driven. Local water management groups would be in a position to make informed decisions based on the resources and requirements of their basins. In most instances, specifically in arid developing countries, it will be financially more viable to rely on the trade domain of the cycle. As users would be charged a market related price for the water they receive it will quickly become apparent which options make sense in terms of overall costs and benefits.

Individuals, who under the hydraulic mission had relatively little control over how water resources are managed, are able to exert a far higher level of control over the trade domain of the cycle. Engineering schemes to transfer water from one basin to another typically require huge amounts of funding and cannot be bought in discrete "packages". The whole scheme has to be completed for the water to flow. Virtual water on the other hand can be bought in small quantities – in accordance with the ability of the basin population to pay for imports. In future work on the hydrological cycle there should be an effort to incorporate the costs and benefits of the various domains involved. This would provide water managers a clearer indication of the various options open to them, allowing them to tailor-make solutions to the region in which they are operating.

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