Defining sustainable yields for rainwater harvesting

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Abstract
The paper discusses the special characteristics of rainfall, runoff and groundwater recharge in arid areas and identifies the challenges to define sustainable yields for rainwater harvesting systems. Rainfall is commonly highly variable in space and time, which has led, for example, to the use of dispersed surface water storage systems to support nomadic agriculture. Many rainwater harvesting systems rely on exploitation of groundwater, augmented by active recharge of surface water. This depends on the integrated management of surface water and groundwater systems. To quantify sustainable yields requires assimilation of rainfall variability, runoff processes and surface water-groundwater interactions. A distributed modelling framework to achieve this is described, with application to the assessment of sustainable yield of recharge dams in the Sultanate of Oman.

1. Introduction to rainwater harvesting
Rainfall harvesting is a term that is widely used, but encompasses a range of very different techniques and technologies, applied across a wide range of scales. At its simplest, it describes the direct capture of rainwater as surface runoff. This may be runoff from roofs and paved areas, harvested at the scale of an individual household for domestic use, surface runoff from small natural catchments, directed to cisterns or tanks for community use, or spate flood flows diverted from a wadi channel to irrigate whole fields. Rainwater harvesting is also used to describe the modification of hydrological response, to provide additional water for subsurface storage. At a local scale, terracing or micro-catchments may be used to reduce surface runoff and increase infiltration to increase available soil moisture for agricultural use. Alternatively, at catchment scale, groundwater recharge can be enhanced and/or focussed – for example through the use of ‘recharge dams’ to retain or retard surface water flows so that infiltration can be enhanced and/or directed to recharge an aquifer system.

2. Sustainable yields and rainfall temporal variability
While much attention has been focussed on methods of rainfall harvesting, and their local performance, relatively little consideration has been given to the sustainable yield of rainwater harvesting systems. For simple systems, such as the capture of roof runoff, sustainable yield will depend primarily on the temporal variability of rainfall. However, rainfall in arid areas, although by definition limited in amount, is in addition characterised by extreme variability. Where convective rainfall predominates, storm intensities can be high - it is not uncommon in Arabia or the South West of the USA for rainfall in a single storm to exceed the average rainfall for a year (Wheater, 2006). Inter-annual variability is also high; mean annual rainfall is often not a meaningful indicator, and persistent sequences of dry years can occur. For simple rainwater harvesting systems to provide a sustainable resource, therefore, the intermittency of rainfall and its inter-annual variability must be recognised within a frequency-based approach to drought risk and reliability. To accommodate drought, simple systems of surface runoff storage will in general need to be seen as one element in a more comprehensive set of water supply options.

3. Managed groundwater recharge
Given the high potential evaporation rates that occur in arid areas, the most attractive large-scale options for increasing available water generally make use of the available subsurface storage in aquifer systems, and there is increasing interest in, and development of, groundwater recharge management systems. For example, the Sultanate of Oman has, over the last 20 years, invested in
recharge dams on the Batinah coastal plain of Northern Oman. These storages are designed as dams with restricted discharge outlets to retain water behind the structure and slow the downstream transmission of flood water. Thus groundwater recharge is focussed both behind and immediately downstream of the dam. In the case of coastal aquifers, such structures capture runoff that otherwise may have been lost as surface runoff to the sea, and the enhanced recharge is important in combating problems of saline intrusion. In other locations, the ability to focus recharge creates the opportunity to enhance a resource at a location that may be of interest due to the availability of aquifer storage or of local demand. To assess the sustainable yield of such systems is complex. Management options must be evaluated at catchment scale, so that any redirection of resource can be considered in the context of existing sources and associated water rights, and a number of important technical issues arise.

4. Spatial variability of catchment-scale hydrological response

For rainwater harvesting applied to the larger spatial scales it is necessary to understand the spatial variability of response of surface water systems, the underlying groundwater response, and the interactions between surface water and groundwater. Groundwater quality considerations may also be important. For a detailed review of hydrological processes, see Wheater et al. (2006); a brief summary of relevant issues is presented below.

Comprehensive monitoring of surface and groundwater systems is relatively rare – or at least is relatively rarely reported in the published literature. However, there are notable exceptions, particularly the long-term densely monitored Walnut Gulch catchment in Arizona, USA (see for example, Osborn et al., 1979, Lane et al., 1971, Goodrich et al., 1997). In the Middle East, the Five Wadis Representative Basins Study in the South West of Saudi Arabia, undertaken in the 1980s, deployed networks of climate, rainfall, flow, soil moisture and groundwater recorders. The most striking result was the picture that emerged of the spatial variability of the predominantly convective rainfall. Rainfall was intense, of short duration, and highly localised in space (Wheater et al., 1991a,b), generating runoff on partial areas of the catchment even on days of relatively widespread rainfall. Surface runoff was focussed in alluvial wadi channels, and transmission losses from surface routing provided infiltration to recharge alluvial groundwater. Thus floods would tend to decrease in volume as the flood peak progressed downstream. These responses are very similar to those observed from Arizona, and the combination of rainfall spatial variability and transmission losses explains the well known property of arid zone catchments of decreasing runoff yield with increasing catchment area.

Clearly, attempts to quantify the potential for water harvesting through managed aquifer recharge in this environment requires that the spatial characteristics of rainfall, and hence runoff generation, are recognised, as well as the surface water-groundwater interactions that determine transmission loss and managed recharge.

5. Defining sustainable yields for managed groundwater recharge

In a study of the potential resource yields from a proposed recharge dam in a wadi system in Northern Oman, Wheater et al. (1995) developed a modelling framework to capture the spatial variability of rainfall, runoff generation and groundwater recharge. This required a stochastic rainfall generator that was developed empirically from the available raingauge network (modelling the probability of rainday occurrence and the conditional distribution of rainfall spatial occurrence and depths by sampling from the population of observed events). This was used with a specially-developed rainfall-runoff model that used SCS curve numbers to generate the spatial distribution of runoff (with parameter spatial distributions developed from soils and geology) and flow routing in the wadi channel network, including transmission losses (after Jordan, 1977). In principle, such a model could then be combined with a groundwater model to represent aquifer response. Within the distributed rainfall-runoff model, it was possible to explore the response to recharge dams of different sizes and locations, for a sequence of years of stochastically-generated daily spatial rainfall inputs. Hence the potential yields of alternative designs could be evaluated in a risk-based framework, considering for example yield for drought sequences of differing severity.
6. Concluding discussion

For simple small-scale rainwater harvesting systems, the definition of sustainable yields will depend on evaluating rainfall variability within and between years, with sequences of drought years being of particular concern. For larger-scale rainwater harvesting systems, the spatial patterns of runoff generation and resulting transmission losses are also important. These define the scale-dependence of available runoff for spate irrigation, for the management of surface flows and of groundwater recharge.

A modelling framework to achieve this has been outlined, developed for a case study application to recharge dam yield evaluation in Northern Oman. By considering modelled response to multi-year spatial rainfall sequences (which could be based on observed rainfall or stochastically-generated rainfall), a risk-based assessment of sustainable resource yield can be carried out.

Such modelling is in its infancy and needs to be developed further. The stochastic modelling of spatial rainfall in arid areas has received little attention, and the method described above could be improved. However, recent work to develop spatial rainfall simulators for more humid climates (Chandler and Wheater, 2002, Yan et al., 2005) has led to tools that can also be linked to GCM and RCM scenarios of future climate, and hence evaluate response to climate change. Climate change issues are clearly important, and cannot now be neglected in developing plans for sustainable water resource management. Quantification of transmission losses is achieved using a simple model, with appropriate complexity for this purpose. However, controls on transmission losses are not well understood, and more work to quantify these experimentally is needed.

This paper has focussed on the quantification of sustainable yields from rainwater harvesting systems. It should be recognised that other aspects of sustainability are of equal importance for rainwater harvesting – ranging from technical issues such as the management of sediments in harvesting systems, to socio-economic issues such as the ability and incentives to maintain those systems. These issues are of course intimately related and ultimately the viability of such systems depends on the broad economic context defined by government for rural communities.

The above discussion has focussed on the management of water quantity. Clearly there is a broader set of issues related to water quality. For certain circumstances, enhanced recharge may be a means of improving groundwater water quality (for example in the remediation of saline intrusion) – alternatively, rising water tables could mobilise natural of anthropogenically-generated pollution. And where active management of groundwater is to be developed, water quality protection will remain important. The modelling framework could also be extended to incorporate issues of land management effects on runoff and recharge. There is concern in many arid and semi-arid areas that degradation of soils and vegetation has occurred. The use of rainwater harvesting techniques to regenerate rangeland areas is one such issue. Modelling systems for integrated catchment management are in their infancy in application to arid and semi-arid areas, but clearly have great potential for informing the development of integrated land and water management and policy.

References


