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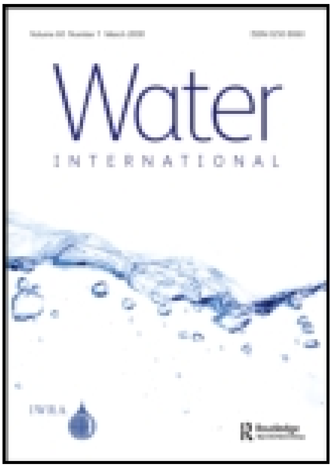

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Local storages: the impact on hydrology and implications for policy making in irrigation systems

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Local storages: the impact on hydrology and implications for policy making in irrigation systems

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OASIS, an irrigation diagnosis model, is applied to the Zhanghe Irrigation System in central China to investigate the contribution of smaller local storages (in “melons on the vine” configuration) as compared with the main reservoir. Results show that local storages are more important in normal-to-wet years, while the main reservoir is critical in dry years, which implies a strong policy correction relevant to many parts of the world. Balanced investment in various storage infrastructures with associated management practices is a cost-effective strategy for irrigation development.

Keywords: hydrology; irrigation; local storages; water reuse; OASIS

Introduction

Hydrology in irrigated areas is strongly affected by irrigation and drainage practices, which makes it difficult to model (Kite and Droogers 1999). These practices, from on-farm soil water management to large-scale water diversions, have different impacts on water-cycling processes; therefore, scale is recognized as a key element in irrigation hydrology (Wallender and Grismer 2002). Water moves across scales and contributes to crop biomass accumulation through the soil–plant–atmosphere continuum. These processes are heavily influenced by infrastructure and management in irrigation systems (Lohani *et al.* 1993, Venn *et al.* 2004, Gosain *et al.* 2005). In addition to direct irrigation supply, surface and subsurface runoff generated from irrigation return flows, together with that of precipitation, are often captured and diverted for further uses downstream. The return flows from irrigation account for about 20–40% of irrigation water supplied (Oosterveld *et al.* 1978, Keys 1981). Estimation of return flows and consequently water reuse is therefore of importance for irrigation diagnosis and performance assessment.

The existence of local storages such as small reservoirs, tanks and ponds adds extra complexity to hydrology in irrigation systems and therefore to the management of water supply. Local storages collect and store surface runoff, including irrigation return flows, which affects the flow convergence process. This function makes it possible for water “losses” upstream to be re-used in downstream areas (Roost *et al.* 2008a). The local storages can be operated either separately or through connections to main irrigation canals. The latter forms the “melons on the vine” system used in China. Such systems add flexibility

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to irrigation and drainage management, and help farmers cope with dry spells before irrigation supply reaches their fields (Wang 1984). The operation principles of such systems, however, evolve over time. In the Zhanghe Irrigation System in Hubei, central China, farm ponds constructed by individual farmers have received constant development in parallel with government investment in the main reservoir and canal system. This movement is a response to the decentralization of irrigation management and the introduction of water pricing imposed for the main canal supply (Mushtaq *et al.* 2009). Farmers invest in developing their own water resources, which they see as more reliable and cheaper (Mushtaq *et al.* 2007). The change is recognized by irrigation managers and policy makers. However, due to the fragmented nature of these small storages and lack of understanding of their impact on hydrology, it remains unclear how to consider them in current management and investment systems.

The main objective of this paper is to provide evidence-based policy recommendations for irrigation development with appropriate investment and management strategies on irrigation infrastructure including local storages. A combined approach to access return flows, irrigation water reuse and their impacts on hydrology through conjunctive modelling of canals, drainage and local storages is tested in the Zhanghe Irrigation System. Scenarios on alternate irrigation development strategies are analyzed to examine the role of local storages and explore their implications for policy making.

The study area

The Zhanghe Irrigation System, served by a 2 km^3 multi-purpose reservoir, is located in the Yangtze River basin, central China. The geographic extent of the irrigation system is 5540 km^2, mainly laid out in hilly areas (Figure 1). The area receives an average annual rainfall of 960 mm, close to 60% of which occurs between May and September. Around 29% of the command area was designed to be irrigated with supply from the reservoir. However, the actual irrigated area has shrunk significantly. Rotation of irrigated rice in summer and rainfed rapeseed in winter is the predominant cropping pattern in the region.

The system is characterized by numerous local storages, including small to medium-sized reservoirs. It was reported that there were 31,150 ponds and 9 medium reservoirs in the command area of the third main canal of the Zhanghe Irrigation System alone. The storage capacity of these ponds totals 106 million m^3, which accounts for 60% of the annual average irrigation water supply from the main reservoir. These storages, scattered throughout the system, play a key role in capturing runoff and providing irrigation during dry spells (Roost *et al.* 2008b).

The large Zhanghe Irrigation System is considered a “model” in China with a high level of irrigation water management and has been well studied. Long-term trends on crop production and irrigation-water diversion suggest that the performance of the irrigation system has steadily improved over the years (Molden *et al.* 2007). During the turbulent period of 2002–2004, when a “fee to tax” policy (which cut funds to local water management agencies) started to be implemented in the Zhanghe Irrigation System, many tertiary canal mangers stopped organizing irrigation supply because they were no longer being paid the water fee. Consequently, the water in the reservoir could not be allocated to farms in need of water. The irrigation release in 2002 was only 5% of a normal year, even though it was a relatively dry year. However, the system sustained high crop yields similar to normal years. This surprisingly low input–high output situation poses an interesting question for irrigation mangers: what made the system successful in coping with the man-made drought?

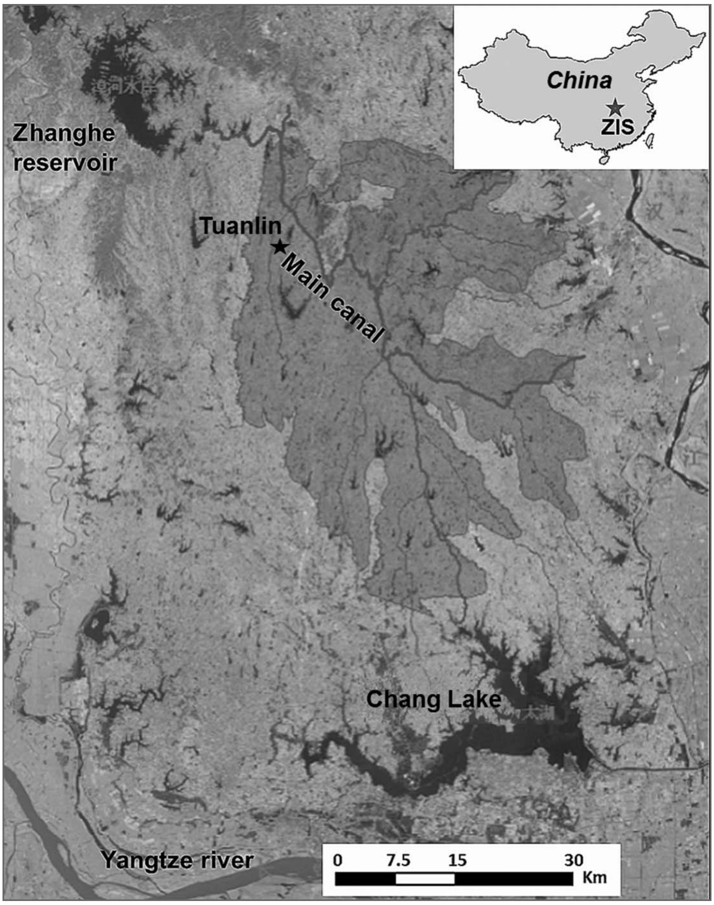

Figure 1. Location of the Zhanghe Irrigation System and the selected study area.

Methodology

The OASIS model

OASIS is a planning tool for medium-to-large-scale canal irrigation systems. It specifically takes account of surface–groundwater interactions to assess the impacts on water use, depletion and productivity of a broad range of interventions in irrigated agriculture. OASIS is based on water balance and includes a strong management component. The main innovation of the model lies in its capacity to capture irrigation return flows and integrate recycling of water through conjunctive drainage and groundwater use (Roost *et al.* 2008a).

The OASIS model includes local storages in the water recycling processes. A virtual reservoir with capacity equal to the sum of all storages within each simulation unit is used to represent the actual situation. The characteristics of the virtual reservoir are determined through spatial analysis, which includes drainage areas and storage capacity. Virtual reservoirs are equally accessible to all areas within the unit. The geometry is described in Equation (1):

$$A = a \cdot K^{1/a} \cdot V^{(a-1)/a} \tag{1}$$

where A is the water surface area; V is the storage volume of the virtual reservoir in m^3; and K and a are two shape parameters. Virtual reservoirs in OASIS play a central role in water reuses. The return flows through surface and subsurface drainages are captured by them. The reservoirs also have a set of user-defined management rules which guide the reservoir operations in collecting return flows and supplying water for irrigation.

Water movements in the storage cascade system involve complex processes. Figure 2 illustrates the process of water cycling in a cascade system. Runoff is captured by individual ponds, which is then redistributed to downstream farms. Part of this water is captured again by downstream ponds. This process keeps repeating until the water finally flows out of the cascade, i.e. the last pond. Water in this case is highly regulated and intensively reused.

The water balance of a sample cascade is determined based on field monitoring and water accounting. Jayatilaka *et al.* (2003) estimated pond water balance using a simplified approach to determine water availability in an irrigation tank cascade system. The present study modifies the model to account for the daily water balance of the three monitored ponds as expressed in Equation (2):

$$V_{i+1} = V_i + R \cdot A + In - E_0 \cdot A - L \cdot V_i - Irri \qquad (2)$$

where V_{i+1} and V_i are pond water volumes on day $i+1$ and day i respectively (in m^3); R is the direct rainfall on the pond surface (m); A is the pond surface area (m^2); In is the sum of surface and subsurface inflow to the pond (m^3); E_0 is open water body evaporation (m); L is the coefficient of water losses due to percolation and seepage; and $Irri$ is the pond irrigation release on day i (m^3). In Equation (2) daily irrigation release is measured and pond water volume is calculated using a depth–volume rating curve with daily water-level measurements. IU43 represents a typical situation that it is mainly supplied by the main canal system but also receives return flows from IU42 and drainage networks. Daily rainfall and pan evaporation records measured at the Tuanlin Irrigation Experiment Station (Figure 1) were used directly to feed into the model. Two variables remain to be determined: daily inflow and losses (from percolation and seepage). During dry spells there is no surface flow into the pond and subsurface inflow reaches minimum values (base flow). However, this base flow has no impact on pond water balance because there is always a corresponding amount going out of the pond. Therefore, the percolation and seepage losses excluding

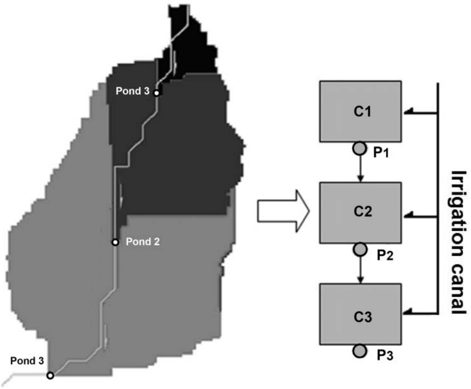

Figure 2. Schematization of the pond cascade. The three ponds are connected to each other; the downstream ponds collect return flows from their catchments and from upstream ponds.

base flow could be estimated as pond water reduction minus evaporation. As ponds are often small in size and the rice growing season is limited to approximately three months with similar weather conditions, this loss rate is assumed to be constant all through the rice growing season. Daily inflow *In* is then estimated by solving Equation (2).

Return flow within a cascade is calculated based on the water balance components. A significant amount of water into the cascade system, both from irrigation supply and rainfall, is captured and consumed through evaporation or transpiration, or lost to deep percolation. Some water, however, travels through and joins the drainage networks, and is then captured by local storages such as ponds. The same process occurs again further downstream when the water is distributed from the pond. The total amount of return flows captured by a cascade can be estimated using equation (3) (Cai *et al.*, 2007):

$$Q_r = \sum_{m=1}^{M} \sum_{n=1}^{ndp_m} (A_m \cdot q \cdot \eta^{n+1} \cdot \mu^n) \tag{3}$$

where Q_r is the accumulated return flow captured by ponds given q metres of water input (including irrigation and rainfall); M is the length of the pond cascade (number of ponds connected to each other); A_m is the catchment area of pond m; ndp_m is the number of downstream ponds of the same pond (it also represents the probability of water being captured again by other ponds); η is the coefficient of returns of an individual pond (calculated as pond inflow divided by catchment inflow); and μ is the pond water supply efficiency (calculated as pond water supply divided by total pond water inflow).

The OASIS model was set up for a sub-catchment area within the Third Main Canal of the Zhanghe Irrigation System. This 325 km^2 area is in close proximity to and served by the main canal. It also has two medium-size and a number of small reservoirs which provide water supply to neighbouring farm fields. GIS spatial analysis was performed to divide the area into 14 irrigation units (IU). These IUs were connected to each other through irrigation and drainage segments (Roost *et al.* 2008a).

Model calibration using field monitoring and remote sensing data

Model calibration was carried out with a combination of field observations and satellite estimates. The daily water table of a pond cascade with three ponds located in IU 2 was monitored. Weather data including temperature (minimum, maximum, average), humidity, sunshine hours, precipitation and pan evaporation were recorded at Tuanlin Station, 1 km away in IU 3. Irrigation inflows were measured at canal outlets. The accounting of water balance for the ponds provides parameters such as number of refills, return coefficient (pond water inflow divided by the sum of irrigation and rainfall in the catchment) and pond water reuse efficiency (pond water supply divided by pond water inflow). Detailed description is beyond the scope of this paper but can be found in Cai *et al.* (2007).

Actual evapotranspiration (ET) estimated through a remote-sensing approach was used to calibrate the OASIS model. A simplified surface energy balance (SSEB) model was employed to estimate ET from two Landsat images and 15 MODIS images (Cai and Cui 2009). The ET values as summarized for each IU were used as reference values to calibrate the modelled evapotranspiration.

Scenario analysis

The turbulent years 2001 to 2004 were identified as a good simulation period to address the research questions raised above. This period not only contains a wet year in 2004 and

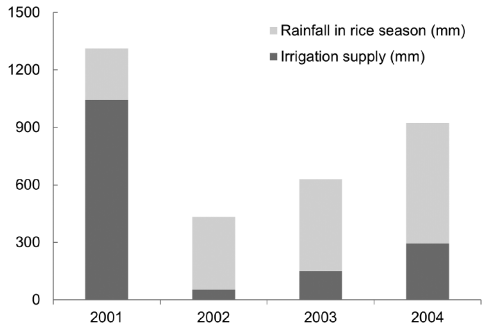

Figure 3. Irrigation supply and rainfall over the rice growing season (May 21–Sept 10), 2001 to 2004.

a dry year in 2001, but also witnessed a sharp decline in main canal irrigation supply in 2002, with recovery in 2003 and 2004 (see introduction). The gross inflow decreased significantly from 2001 to 2002 (Figure 3), yet crop yields in 2002 were consistent with those in other years. This change provides a good opportunity to examine the contribution of local storages in helping farmers cope with water shortage. The model was set up with this baseline situation.

Two additional scenarios were developed. Scenario 1 is to reduce the storage to half of the current value; Scenario 2 is to remove all the local storages. These scenarios help to assess the contribution of local storages in comparison with the main canal supply.

Results

Model calibration

Estimates of ET based on remote sensing significantly improved the ET module of the model. A series of parameters including crop coefficient and soil profiles were adjusted to match the modelled ET with remotely sensed ET values. This process eliminated approximately 50% of the initial difference. The ET estimated from remote sensing had good agreement with that from the OASIS model after calibration. It also greatly improved the accuracy of ET from different land uses. The model performs relatively well for normal events such as irrigation and moderate rainfall, although its capability of capturing storms is limited.

Characterization of storages and return flows

Ponds in the study area are densely distributed and well connected. Satellite images show 2795 storages, most of which are ponds, within an area of 71 km^2. About 93% of these storages fall in the catchments of one or more other storages. The average length of storage cascades, that is the number of storages connected to each other, is 5.75, with the longest found to be 17. The spatial distribution of ponds showed no apparent pattern, but the length of the pond cascades, which indicates hydrological connectivity, shows a declining trend as slope increases (Figure 4).

Daily water balance components for Pond 2 are plotted in figure 5. The study area received two irrigation supplies: one in June and one at the end of July and beginning of August. The pond water volume curve responds well to the supplies and rainfall events.

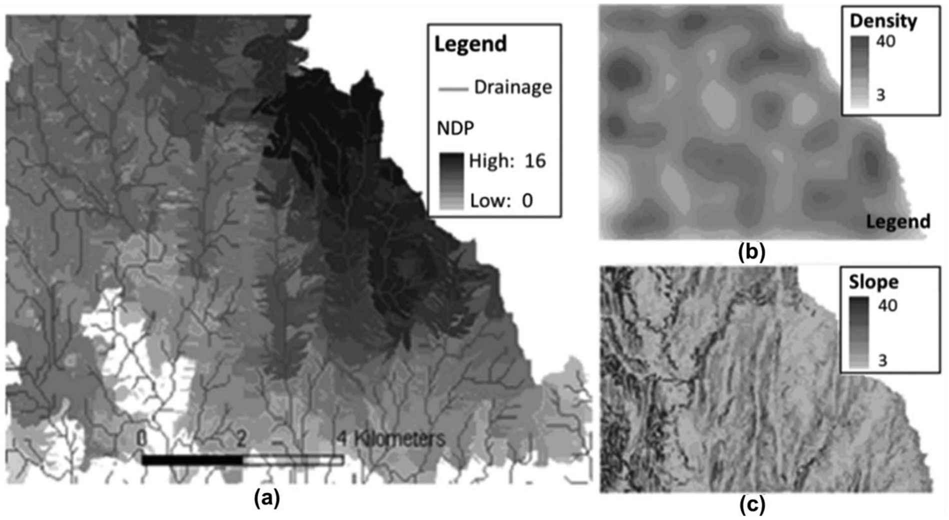

Figure 4. Characteristics of pond cascades in the study area: a. spatial distribution of number of downstream ponds (NDP = cascade length – 1); b. pond density (number per km^2); c. slope (degrees).

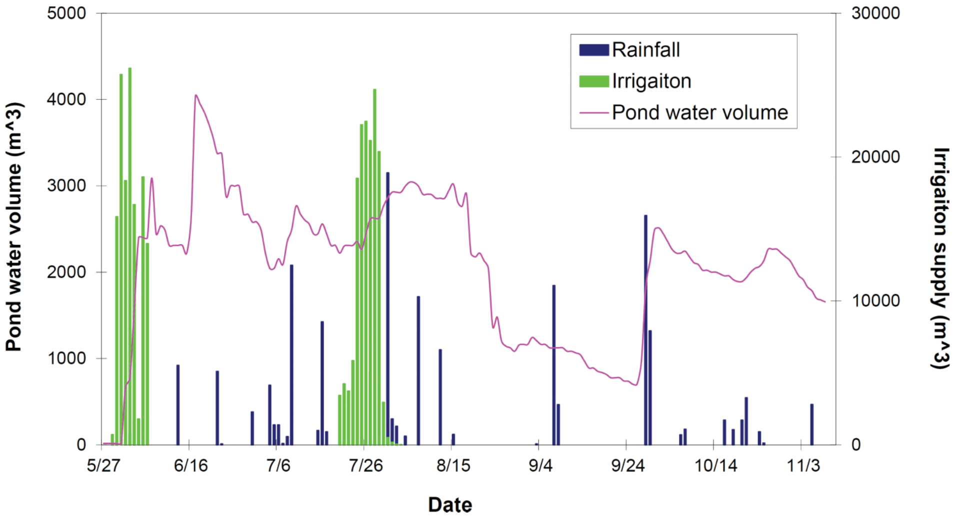

Figure 5. Observed daily water volume, irrigation and rainfall for Pond 2.

A dry spell in September lasted for 3 weeks. The percolation and seepage coefficient was estimated to be 0.9%, 1.5% and 1.3% for the three ponds respectively.

Water balance of the three ponds for the rice growing season (21 May–10 September) is summarized in Table 1. The gross inflow (rainfall plus irrigation) to the cascade catchment is 873 mm. The average return coefficients of individual ponds for rainfall and irrigation are 20.9% and 16.1%, respectively. Pond 1 has a much higher coefficient of returns. This is because this pond has a lower percentage of paddy fields, which means less water consumption, in its catchment. It also serves as a fish pond. More active water collection

Table 1. Summary of pond water balance and the return flows for the rice growing season.

					Percolation		Rainfall			Irrigation			Irrigation release	
Pond ID	Storage (m^3)	Surface area (m^3)	N^*	E_0 (mm)[†]	Depth (mm)	L (%)	Depth (mm)	Returns (mm)	η (%)	Depth (mm)	Returns (mm)	η (%)	Depth (mm)	To returns (%)
1	2,372	20,230	1.95	36.6	67.2	0.9	467.2	132.5	28.4	405.8	95.9	23.6	124.2	54.4
2	4,100	96,440	2.66	18.7	30.4	1.5	467.2	61.1	13.1	405.8	52.0	12.8	57.1	50.5
3	21,603	235,920	1.59	14.0	116.1	1.3	467.2	97.8	20.9	405.8	48.1	11.9	46.7	32.0
Avg.	9,358	117,530	2.07	23.1	71.2	1.2	467.2	97.1	20.8	405.8	65.3	16.1	76.0	45.6

*Number of refills for ponds.

†Water volume expressed in depth corresponding to pond catchment area.

practices are conducted for this pond. The total water returns of the pond cascade are calculated using Equation (3). The accumulated return flows from rainfall and irrigation are 126.1 mm and 85.2 mm, respectively. The coefficients of return for rainfall and irrigation are 27.1% and 20.7%, respectively. Both figures are higher than those of individual ponds.

Pond water supply is, however, significantly lower than that captured by the ponds. The total water captured by ponds is estimated to be 23.1 million m^3. The effective water supply from the ponds is estimated to be 10.5 million m^3, only 45.6% of the captured water. This supply accounts for 21.8% of the total irrigation supply to the study area. Although the average number of refills for the three ponds is 2, a significant percentage of water is lost to open water evaporation and percolation from the ponds.

System water balance

Model results for the baseline and different scenarios are summarized in Table 2 for the system and selected IU 43. It is observed that at the system level, the ET and yields of rice in the four different years are similar (baseline scenario). This is remarkable, because rainfall and irrigation supply fluctuate significantly in the same time frame. Water supply from local storages remained high through 2001 and 2003. However, the outflow shrank significantly in 2002, making more water available for rice consumption. It should be noted that open water bodies consume a certain amount of water through evaporation. The key elements of IU 43 are also listed as example. Canal supply into this unit is much lower than the system average value. However, a large volume of return flow from the upstream unit is observed. IU 43 is located in a downstream area. It receives a lot of return flow, so the farmers order less water from the main canal. In 2002, both the return flows entering IU 43 and the outflows leaving IU 43 were generally lower than other years. Water productivity values of summed irrigation supply and rainfall for year 2002 are considerably higher than those of other years.

The two alternate scenarios showed opposite trends in crop yields and outflows. When there are no ponds, crop yields are significantly affected, except in the wet year, 2004. Due to the lack of storage, the outflows are much higher than those in the baseline scenario for all four years. When water supply from the main reservoir is removed, crop yields are hardly affected in 2002 through 2004. The dry year 2001, however, shows a 25% drop in the crop yield. Local supply by ponds has slightly increased as a result of zero supply from the main system. Farmers respond to the water shortage by drawing more water from the ponds. It is also interesting to see that the outflow in the years 2002 to 2004 is similar to or higher than in the baseline scenario. This is because the interception of rainfall by storages has reached their capacity and the excess rainfall can no longer be stored. In the No Zhange Irrigation System scenario, water productivity (WP) increased by one-third compared with the baseline scenario. It almost doubled in the dry year of 2001. This is a result of decreased yield and significantly reduced water supply.

Discussion

Local storages have significant impact on water cycling processes and water balance. Both the sizes and the distribution of storages have impacts on hydrology. The densely distributed ponds in the Zhanghe Irrigation System capture a significant proportion of irrigation return flows and rainfall runoffs. When storages are connected to each other and make up cascade systems, the capacity to regulate flows increases significantly. Most of the water captured by storages was consumed through evapotranspiration by farms, which is

Table 2. Key model water balance components of the system and selected irrigation unit (43) under different scenarios for the rice growing season.

			System							IU 43					
Scenarios	Year	Rain (mm)	Canal supply (mm)	Local supply (mm)	Outflow (mm)	ET_ rice (mm)	Eo_ ponds (mm)	Relative yield	WP_I+R (Kg/m^3)	Canal supply (mm)	Local supply (mm)	Return flow (mm)	Outflow (mm)	Paddy irrigation (mm)	WP_I+R (Kg/m^3)
Baseline	2001	274.1	510	146	121	377	71	1.00	0.70	148	138	103	236	189	1.23
	2002	382.5	26	143	94	370	76	1.00	1.34	40	138	83	248	142	1.24
	2003	480.5	87	104	243	345	77	1.00	1.04	25	97	154	432	97	1.05
	2004	627.8	161	72	293	319	93	1.00	0.83	28	62	215	565	57	0.88
No ponds	2001	274.1	510	28	265	315	0	0.66	0.46	148	61	144	353	146	0.94
	2002	382.5	26	30	218	294	0	0.48	0.65	40	76	116	342	94	0.84
	2003	480.5	87	15	320	299	0	0.81	0.84	25	31	171	482	38	0.85
	2004	627.8	161	12	359	318	0	0.96	0.79	28	28	216	566	28	0.85
No Zhanghe Irrigation System	2001	274.1	0	158	92	347	62	0.75	1.48	33	182	53	148	179	1.59
	2002	382.5	0	144	152	365	75	0.97	1.38	24	146	83	247	138	1.28
	2003	480.5	0	116	255	343	77	0.99	1.22	20	98	135	409	96	1.05
	2004	627.8	0	74	297	319	93	1.00	1.04	12	67	166	500	60	0.90

considered beneficial consumption (Molden 1997). A considerable amount of water, however, is lost due to open water evaporation and percolation. This illustrates that although the many local storages in the Zhanghe Irrigation System contribute to improved water use efficiency through water reuses, that does not mean more is better. Improving connectivity of individual storages is a cost-effective approach to maximize the uses of storages, but further complicates hydrological processes in the system.

Local storages are cost-effective in supplying water to crops during normal conditions, but the main reservoir release is crucial during dry years in the semi-humid Zhanghe Irrigation System. In the No Zhanghe Irrigation System scenario, crop yields showed almost no effect, except in the dry year 2001; while in the No Ponds scenario, crop yields fell up to 52%, except in the wet year 2004. This means that local storages are more important in normal-to-wet years while the main reservoir is irreplaceable in dry years.

These findings were not expected by the irrigation system managers, who have regarded the main reservoir as the sole important water source for the command areas and underestimated the contribution of local storages. The policy implications of these findings are significant in terms of future investment and focus. From the policy makers' perspective, the focus of irrigation management has always been on the main reservoir and canal system. This study illustrates the importance of distributed local storages. Compared to the amount of resources required to construct and maintain large-scale irrigation infrastructure, local storages cost much less. In fact, most of the farm ponds in the Zhanghe Irrigation System were constructed by individual farmers with their own labour input. A balanced financial input to maintaining Zhanghe Irrigation System infrastructure (e.g. canal lining) and local storages needs to be investigated, considering economic costs and benefits.

Better understanding of return flows and water reuse helps to diagnose irrigation management for informed policy making. Water depletions from irrigation canals and farms are traditionally considered losses. Quantitative estimation of water reuse helps to assess the actual irrigation requirement and adjust irrigation supply accordingly. Irrigation water is intended to be sent to and kept in farms. But modelling results indicate that the return coefficient of irrigation is only slightly lower than that of rainfall, indicating that the irrigation supply from canals to farms is not well managed. This could be explained by many reasons, such as excess supply, poor condition of the distribution system, less-than-optimal timing or inappropriate canal and on-farm water management practices. The Zhanghe Irrigation System is able to sustain high yields even if the main irrigation supply is cut. This means that irrigation supply to the region has exceeded the actual requirement. Much of the excess water is, however, captured and reused through local storages. This system of water redistribution from storages also changes the spatial and temporal water requirement and could be used to expand actual irrigated areas. This includes not only further downstream areas but also high-elevation islands that are not being served by the canals. Because of the local supply, the requirement for main canal water is delayed. Such information is valuable for irrigation mangers in allocating the proper amount of water at the right time.

Real water saving could be assessed from the explicit water accounting including return flows. The OASIS model incorporates a water accounting framework developed by Molden (1997). At small scales, water accounting through selected pond cascades reveals only 10% of the losses from irrigation supply. The ratio of system outflow to gross inflow varies from 15% to 43%. It is not possible to estimate the irrigation water use efficiency precisely because of the difficulty of separating return flows of rainfall from those of irrigation at system level. Nevertheless, it is already higher than the 39% irrigation efficiency reported by the Zhanghe Irrigation Administration Bureau.

Water productivity is a useful indicator with which to assess irrigation performance, but the indicator itself is not the target of irrigation water management. In the No Zhanghe Irrigation System scenario, WP improved significantly, which correctly reflects the reduced water inputs and higher water use efficiency. However, this is not always desirable, particularly when water is abundantly available. Improving WP is only warranted if it serves the goal of improving land productivity while conserving the environment.

Conclusions

Local storages, including small-to-medium-sized reservoirs and farm ponds, play an important role in capturing and reusing irrigation water. The contribution from local storages has hydrological, management and policy implications for irrigation development. They store water in times of excess and provide supply during dry spells. Further, they capture irrigation return flows and make them available for reuse downstream, which improves overall irrigation water use efficiency. Local storages greatly improve the flexibility in organizing irrigation supply and building up farmers' resilience to drought, whether caused by low rainfall or by failure of irrigation delivery from the main canal. The hydrological connections of storage cascades are often ignored, but they provide an opportunity to up-scale water savings from the field level to the system level.

A shift of policy focus on investment and management from the large mono-irrigation system to a balanced canal–local storage system needs to be encouraged. Local storages are a cost-effective alternative or supplement to large-scale irrigation systems. Investment in local storages could help improve individual efficiency as well as increase hydrological connectivity through better planning. Together with physical infrastructure development, the management of water should also involve more local stakeholder consultation processes for coordinated upstream–downstream irrigation water management.

Informed policy making requires understanding of the bio-physical consequences of potential interventions. This paper tries to link the two aspects. Agro-hydrological models such as OASIS, combined with field observations and remote-sensing interpretations, help us to understand hydrological processes, evaluate irrigation water reuses and the contribution of local storages, and weigh the benefits of infrastructure development.

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