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Investigating the potential for efficient water management in spate irrigation schemes using the Spate Management Model

Untersuchung des Potentials eines leistungsfähigen Wassermanagements in Schwallbewässerungssystemen bei Anwendung des Hochwasserleitungsmodells

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Stichworte
Schwallbewässerung, Jemen, Wassermanagement, Hochwasserleitungsmodell.
Keywords
Spate irrigation, Yemen, water management, Spate management model

Zusammenfassung
Unter Schwallbewässerung (spate irrigation) ist hier ein Bewässerungsverfahren oder ein Bewässerungssystem zu verstehen, bei dem quer zu einem gewöhnlich trockenen Wasserlauf Ableitungsdämme aus Erde errichtet werden. Diese Dämme leiten das Schwallwasser über Kanäle zu eingedeichten Feldern, wo das Wasser zurückgehalten wird, bis es verdunstet bzw. versickert und verbraucht ist.

Das Hochwasserleitungsmodell (Spate Management Model (SMM)) wurde entwickelt, um die wirtschaftliche Nutzung von Hochwasser in den Tallandschaften des Jemen zu simulieren. Die durchgeführten Untersuchungen bezogen sich vor allem auf das Wadi Tuban und das Wadi Zabid. Das Modell kann bei dem für die Wadis geplanten verbesserten Wassermanagement hilfreich sein. Es kann vor allem Hilfestellung leisten bei der Erkennung der Auswirkungen von Änderungen von Prozeduren der Wasserzuteilung und -verteilung, und damit bei den Bemühungen zur Optimierung des Wassermanagements von Schwallbewässerungssystemen.

Das SMM kann den Gang und die Verteilung vom Überschwemmungswasser in den Wadiflächen von der Quelle bis zu den Bewässerungsflächen simulieren. Die Stromverteilung bei Umleitungsanlagen und Abflüssen basieren auf den Wasserrechten der Nutzer, dem Fassungsvermögen der Abflussleistung von Kanälen und den Wasserbedürfnissen der Feldfrüchten bzw. der praktischen Anwendung der Hochwässer. Dabei werden Zuleitungsverluste des Wadi und Kanalnetzes sowie die Bewässerungsverluste mit berücksichtigt.

Die Leistung des SMM schließt folgendes mit ein: das Volumen des zu den Bewässerungsflächen umgeleiteten Wassers, die Quantität des noch zur Nutzung verfügbaren Wassers für jede Feldfrucht innerhalb eines Bewässerungsareals (command area), die Quantität des Wassers das schon verbraucht wurde, um die Bedürfnisse der Feldfrüchte zu erfüllen und die aufgetretenen Wasserverluste, die Hochwassermenge, die noch nicht den Nutzungsarealen zugeleitet worden ist und das Überschusswasser, welches aus dem Wadi ungenutzt abfließt (z. B. zum Meer) oder zum Grundwasser gelangt. Der direkte Output vom SMM wird in Tabellen und Berichten zusammengefasst. Das Modell kann ausgewählte Daten für GIS zur graphische Präsentation liefern.

Abstract

The Spate Management Model (SMM) has been developed for the purpose of simulating spate irrigation practices in the flood wadis of Yemen, with emphasis on Wadi Tuban and Wadi Zabid. The model can be used as an aid to decision making in the improved operation and management procedures planned for the wadis. It could also be used to explore the scope for changes to water allocation procedures in order to achieve better water management.

The SMM can simulate the passage and distribution of floodwater in wadi plains starting from the head of the wadi down to the command areas. Flow distribution at the diversion structures and canal offtakes is based on user-defined water rights, canal/offtake capacities, and the crop water requirements of the command areas or spate irrigation practices. Bed losses from the wadi and canal network and the field application losses are taken into consideration.

The output from the SMM includes the volumes of water diverted to each command area, the quantities of water still due to each crop in each command area, the quantity of water that has been used to meet crop water requirements and that that has been lost, the volume of spate water that has not been diverted to the command areas, and the volume of excess flow that may either go to the wadi drainage area (e.g. to the sea) or replenish the groundwater. The direct output from the SMM is in tabular and report formats. In addition, the model can export selected output data to GIS for graphical presentation.

1. History of spate irrigation

Spate irrigation is perhaps the oldest water management and surface irrigation system in the world. Based on archaeological evidence, it is suggested that spate irrigation had started in the Arabian Peninsula, notably in Yemen, where it dates back to 2000 years (FAO, 1987). Trade development and growth after the Islamic period may have helped spread spate irrigation techniques from the Yemen area. For instance, spate irrigation in the Eastern Lowlands of Eritrea is attributed to the arrival of Yemeni migrants some 80 to 100 years ago (HAILE et al., 2003). Nonetheless, because of the diversity and remoteness of some of the areas where spate irrigation is currently practised, it is believed that spate irrigation might have started independently in some of those areas.

Spate irrigation is found in the Middle East, Africa, West Asia, and parts of Latin America. According to FAO Aquastat, a total of 3.15 million ha of spate irrigation are spread over 10 countries (Figure 1) representing 13% of their irrigated areas. The largest areas are in Pakistan and Kazakhstan. However, the data collected by FAO is based on government statistics. It is believed that more informal areas of small-farm spate irrigation can be found in other countries such as the Sudan, Ethiopia, Egypt, Kenya, Mauritania and Senegal as well as Chile and Bolivia.

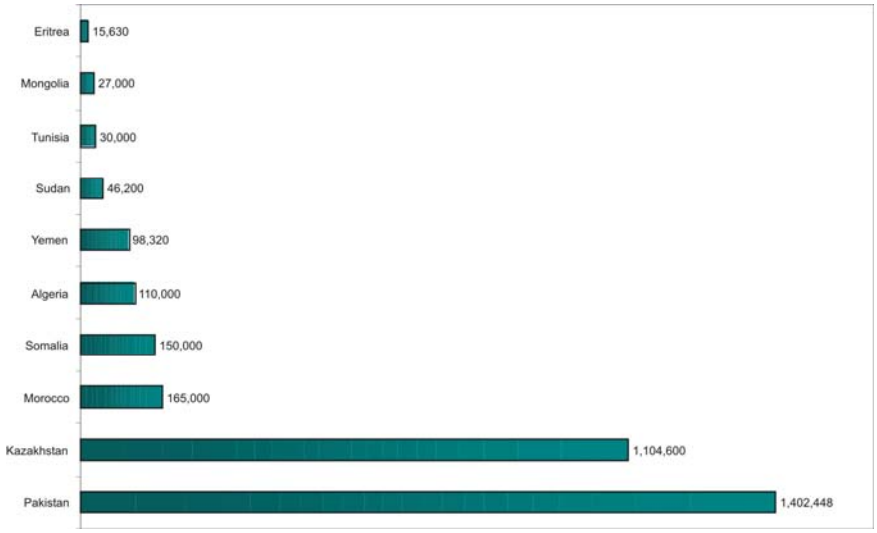

Figure 1:
Spate irrigation areas, ha (FAO Aquastat)

2. Spate irrigation

Spate irrigation is usually practised in semi-arid environments. Rainfall over mountainous catchments forms spate floods that run through the generally dry wadi beds towards wadi deltas. Spate irrigation involves the diversion, conveyance and application of those spate floods to the irrigated lands in the wadi deltas. Simple earthen, brushwood, gabion or concrete structures are used to control spate water. The earthen and brushwood structures are usually built by the farmers themselves from local material. They have proved to be effective and durable to control low to medium floods for a long time. Water is applied to bunded fields often once before crop planting only. The average application depth is large enough (around 0.5 m or more) in order to enable the soil retain enough moisture that can meet crop water requirements throughout the usually dry growing season.

By nature, spate irrigation is prone to high risks and uncertainty. First, there is the uncertainty of spate floods that in dry years there might be too little or no flood water to grow any crops. Second, there is the risk of exceptionally large floods that can cause substantial damage to the water diversion structures and conveyance system. Third, there is the risk of high sedimentation that can settle in the canals and in the fields. Some fields in Yemen have accumulated too much sediment to the extent that

they became very difficult to command. All these factors make spate irrigation mainly a subsistence activity, with low returns, highly variable incomes between good and bad years, and high labour input for operation and maintenance, which is essential for the sustainability of the system. Subsistence crops, often sorghum, are mainly grown if spate water is the only source of irrigation.

3. Yemen agriculture

Yemen has a predominantly semi-arid to arid climate. High temperatures prevail throughout the year in low-altitude areas (e.g. the western and southern coastal plains) whereas greater variations in the temperatures can be experienced in high-altitude areas. Rainfall is highly erratic in time, quantity and location. There are two main rainy seasons in Yemen; the first from March to May (*Seif*), and the second from July to September (*Kharif*), with the latter being wetter than the former (VAN DER GUN and AHMED, 1995).

The total area of Yemen is about 55 million ha, most of which are barren mountains and deserts with some wadis in between. About 1.7 million ha (2.5% of the country's area) is potentially cultivable (CSO, 1995). However due to the scarcity and variability of the water resources, the average annual total cultivated area is not more than 1.1 million ha. In wet years with well-distributed rainfall, the total cultivated area could reach 3.5 million ha.

Traditionally, the predominant farming systems in Yemen were spate and spring irrigation, terrace agriculture, and rainfed fanning in the plains. In the last twenty years, tubewell irrigation has become the most important contributor to agricultural output, and now occupies 34 percent of the cultivated area (WB, 1997).

The conjunctive use of spate and ground water can greatly improve the productivity of spate irrigation schemes in terms of both quantity and quality. For instance, it is noted that in Yemen farmers who could afford the cost of groundwater (either by installing their own wells or by buying the water from nearby well owners) usually shift to growing more cash crops, especially fruits that are exported to neighbouring Gulf countries.

The main drawback is the rapid depletion of the groundwater resources due to the unregulated and excessive use of the resource. The groundwater in Yemen is not used by agriculture only, but it is the main source of water for major cities such as Sanaa and Taiz. The rapid depletion of the resource does not affect the rural areas only but also the livelihood of some urban centers.

Of the arable crops grown, cereals dominate and occupy about 18% of the cultivated area while fruits and forages/forests occupy 5% and 3% respectively. On the other hand, the areas cultivated with *qat* have recently increased because of its high value in the local market, despite of its high water consumption (AQUASTAT, 2003).

Agriculture was and still is the backbone of Yemen's economy. In 2001, it contributed nearly 20% of the gross national product (GNP), provided employment to over 16% of the country's workforce and livelihood for all the rural residents – who constituted nearly 76% of the total population (CIA, 2003).

3.1 Spate irrigation in Yemen

Spate irrigation in Yemen covers 120,000 ha (or about 11% of the average cultivated area) of which the major modern schemes cover about 90,000 ha. These are distributed among seven main wadis in Yemen; namely Mawr, Bana, Zabid, Tuban, Hassan, Rima and Siham (WB, 2000). The flood water in these wadis is not only vital for irrigation but also for domestic and industrial uses, with the last two uses depending mainly on the groundwater stored in the delta alluvium of the wadis.

A very specific feature of traditional spate irrigation in Yemen, as well as in other areas of the world, is the existence of several types of water rights and rules that govern the distribution of flood water among irrigated lands. Some of the most common rules are (AL-SHAYBANI, 2003):

– Upstream right to water: The lands are irrigated in turn from upstream to downstream. Upstream lands are fully irrigated first before the downstream ones can take any spate water. Nonetheless, in wadis with extensive irrigation networks; such as Wadi Zabid, Wadi Rima, Abyen and Tuban Delta; there are also additional local water laws which to some extent put restrictions on upstream landowners.
– Land priority: The areas that come under agriculture first establish priorities in the right to water so they have precedence in irrigation by seasonal flood flow.
– Calendar dates: In large wadis, such as Wadi Zabid, spate water distribution among top, middle and tail areas of the wadi delta is carried out based on calendar dates.
– First floods: Sometimes there are separate rules for the right to water from the first flood(s) in the season. For instance, only areas cultivated with trees might be entitled to take water from the first floods.
– Application depth: The right to irrigation is sometimes governed by the depth of application. The maximum allowable depth of water per season could be fixed to all the areas irrespective to the irrigated crop, or it could be variable depending on crop type.
– Water availability: Some downstream areas might have the right to spate water only if the water available at upstream areas exceeds certain quantity (usually controlled by water depth).

It is usually the case, especially in large schemes, that more than one rule are applied simultaneously. Generally, the water rights are well-established and respected in spate water distribution, however, it is also common that influential farmers try to and do break those rules sometimes.

3.2 Yemen spate irrigation improvement

In realising the importance and value of spate irrigation as an indigenous irrigation technique in Yemen, the Government started several projects for reconstruction of spate irrigation systems in the 1980's. The main goal of these projects was to ensure the sustainable management and use of water resources and to increase agriculture productivity and hence improve the livelihood of the poor smallholders. A large number of spate systems were rehabilitated/modernised – particularly in the Tihama Plains and around Aden. The Government made the large investments required for rehabilitation/modernisation, and subsequently assumed responsibility for their management, with little user involvement or cost recovery.

However, it has become clear that operation and maintenance rather than investment is the main problem. Government strategy has therefore changed in the recent spate irrigation improvement projects to ensure the sustainability of the schemes by involving the stakeholders in development, operation and maintenance through participatory irrigation management (PIM) and cost sharing. The improvement packages comprise the following hardware and software interventions:

– Participatory irrigation management (PIM) and irrigation environmental management, which includes the formation of PIM organizations and improvement of spate management;
– Construction/rehabilitation of permanent diversion structures;
– Rehabilitation and sometimes lining of canals;
– Silt removal;
– Establishment of water user associations and water user groups; and
– Institutional strengthening and capacity building, including change management and training.

The Spate Management Model (SMM) was developed for use in the improved operation and management procedures planned for the improved spate irrigation wadis.

4. The Spate Management Model (SMM)

4.1 Overview

The Spate Management Model (SMM) was developed for the purpose of simulating spate irrigation practices in the flood wadis of Yemen, with emphasis on Wadi Tuban and Wadi Zabid. The model can be used as an aid to decision making in the improved operation and management procedures planned for the wadis. It could also be used to explore the scope for changes to water allocation procedures in order to achieve better water management.

Typically, spate irrigation schemes are located in the deltas of flood wadis. A scheme usually consists of the main wadi (flood water course) and its branches (if any), a group of canals for conveying the water from the wadi to the command areas and the command areas where the crops are grown.

The SMM can simulate the passage and distribution of floodwater in wadi deltas starting from the head of the wadi down to the command areas. Flow distribution at the diversion structures and canal offtakes is based on user-defined water rights, canal/offtake capacities, and the crop water requirements of the command areas or spate irrigation practices. Bed losses from the wadi and canal network and the field application losses are taken into consideration.

The output from the SMM includes the volumes of water diverted to each command area, the quantities of water still due to each crop in each command area, the quantity of water that has been used to meet crop water requirements and that that has been lost, the volume of spate water that has not been diverted to command areas, and the volume of excess flow that may either go the wadi drainage area (e.g. the sea) or replenish the groundwater. The direct output from the SMM is in tabular and chart formats. In addition, the output data from the model can be read in GIS software for graphical presentation.

There are two basic uses for the model:

1. As a planning tool: in which case the SMM will be used to advise on the most appropriate operation and water distribution in the wadi over a future period of time, typically one year or more.
2. As an in-season operation tool: in which case the SMM could be given the quantities of water the command areas have received, allowing the outstanding requirements to be estimated, perhaps on flood by flood basis.

4.2 Model concept and calculation methods

4.2.1 Flood flow passage in the water network

A run of the SMM is likely to simulate the occurrence of a flood or a series of floods at the top-end of the modelled wadi delta. Flood hydrographs are defined in the model as date & time-discharge data series. The user defines the time periods of simulation runs (start and end dates).

The SMM simulates the passage of the given flood flows down the wadi and canal network, deducting seepage losses from the flow as it proceeds (other losses such as evaporation losses from the network water surface are ignored). At bifurcation junctions, available flow is distributed among downstream branches according to user-defined criteria, their carrying capacities, and the crop water requirements of the command areas or spate irrigation practices.

4.2.2 Water distribution and allocation rules

An essential characteristic of most spate irrigation schemes is the enforcement of water rights and rules for water distribution and allocation. Similarly, the SMM allows the user to define the rules that govern water distribution to the wadi and/or canals downstream from bifurcation points as follows:

– Priorities: each wadi or canal reach downstream from a bifurcation point can be given a priority that defines its turn in water allocation. In such cases, water is allocated to the wadi/canal with the highest priority first until the full demands of its command areas are met, and then the remaining water is allocated to the wadi/canal with the second highest priority, etc.
– Shares: each wadi or canal reach downstream from a bifurcation point can be given a share of available water.
– Calendar dates: wadis/canals may be entitled to take water during certain periods of the year only.
– Water availability: wadis/canals may be entitled to take water only when available water is larger than certain quantities.

4.2.3 Water allocation to command areas

The floodwater distributed to the wadi and canal network is allocated to the command areas according to their irrigation water requirements and irrigation priorities. The irrigation water requirements of the command areas are calculated according to one of the following user-selectable criteria:

1. Fixed gross application depth per crop (spate): this irrigation method mimics farmer practice in spate irrigation in which a user-defined fixed depth of water is applied to each crop type, provided that water is available to the command area. The target depth of application is applied irrespective to soil moisture conditions on the day(s) of application. The field application efficiency is not accounted for in this case because it is usually included in the defined fixed application depth. In fact, the calculation procedure in this case is reversed such that the actual application efficiency is calculated as the ratio of the volume of spate water stored in the root zone to replenish soil moisture deficit on the day of application to the total applied volume. On the other hand, rainfall is deducted from the required application depth on the assumption that even if the farmers apply fixed water depths, they are likely to reduce the depth of application when it rains. When possible, SMM applies the total required depth of water in the first spate application to the command area. If no sufficient water is available in the first irrigation, additional applications are allocated to the command area until the required depth has been applied (depending on water availability and water rights). When a crop has been fully irrigated with the required depth of water, it is not

irrigated again before a certain number of user-defined days elapses (to prevent repetitive irrigation of upstream command areas).
2. Actual crop water requirements: the depth of water to be applied in any irrigation is calculated based on the soil moisture deficit on the day of application after deducting the rainfall, if any, and allowing for the average field application efficiency.

Command area irrigation priorities govern how water is allocated to the command areas that feed from one wadi reach or canal. If more than one command area feed from the same canal reach, flood water in the reach is allocated to the command area with the highest priority first until its full demands are met and then the remaining water is allocated to the area with the second highest priority, and so on.

4.2.4 Crop water use and production

The actual volumes of water allocated to each command area are used to maintain a daily soil moisture balance for each crop in each command area. The soil moisture balance is used to calculate actual crop water consumption, rainfall water-use efficiency and to estimate potential crop yield. In the soil moisture balance calculations, rainwater takes precedence over irrigation water in replenishing soil moisture deficit. Accordingly, rainwater is assumed to be fully stored in the soil profile until the soil moisture deficit is fully replenished, i.e. no rainfall is lost until the soil profile has been filled with water.

4.3 Data requirements

The SMM requires the following input data:
– Total monthly reference evapotranspiration (ETo) data: either typical values or year-specific data can be entered into the model.
– Crop data: crop name, maximum rooting depth, yield response factor, planting months, growing period, typical spate application depth & monthly crop coefficients (Kc).
– Cropping pattern data (up to four crops for each command area).
– Soil data: soil type and water-holding capacity.
– Daily rainfall data over scheme area: the model can take rainfall data from more than one station if rainfall over the scheme area is not uniform. It should be noted that this data is the rainfall directly over the agricultural area (wadi delta) not the rainfall over the wadi catchment.
– Flood (inflow) data: floods are defined as date & time-discharge relationships. The time step is 15 minutes and the discharges should be divided into base and flood flows. The floods are the result of the rainfall over the catchment area.

– Water network data: wadi/canal reach capacities, lengths, water allocation priorities and water shares. To facilitate network creation, the network is first digitised using a GIS and then the data is imported into SMM.
– Water rights for the canals and the direct offtakes from the wadis.
– Average bed losses from wadi and canal reaches.
– Command area data: total cultivable areas, maximum diversion capacities, typical irrigation efficiencies, water allocation priorities, cropping patterns and soil types.

4.4 Model capabilities and limitations

– The size of the network that can be simulated (i.e. number of network reaches and command areas) is theoretically limited by available computer memory. However, the simulation runs of very large networks are very likely to take long hours. The level of detail of the modelled network should therefore be carefully determined such that very lengthy simulations are avoided while at the mean time the results are not affected by simplifications/omissions in the simulated model.
– The simulated network may have loops, however water is always assumed to flow from the upstream to the downstream end of each network reach (i.e. no negative flows).
– The simulated network may have only one source of surface (flood) water.
– SMM cannot directly simulate the contribution of groundwater to crop water requirements. However, the user may feed the model with such contributions such that it can take them into consideration in related calculations (e.g. estimation of potential crop yield).
– Each command area can have up to a maximum of four crops in its cropping pattern.

4.5 Case study

4.5.1 Wadi Zabid spate irrigation scheme

The spate irrigation scheme of Wadi Zabid in Yemen has been used as a case study for the SMM. Wadi Zabid is one of the seven major wadis draining the mountainous catchment areas down to the Tihama plain land and flows approximately from east to west. The scheme area lies in the eastern part of the Tihama plain, which is located along the coast of the Red Sea. With a command area of about 15215 ha, Wadi Zabid is the third largest wadi in Yemen in terms of net command area after wadi Mawr and wadi Bana.

Wadi Zabid catchment area is about 4,630 km^2. Mean annual rainfall over the catchment is 550 mm. There are two main rainy seasons: *Seif* from March to May and *Kharif* from July to September, with the latter being wetter than the former.

The length of the Wadi delta is about 35 km. The water network comprises the main Wadi and primary, secondary and tertiary earth canals. Water is diverted from the Wadi to the primary canals using five permanent diversion structures (weirs)

across the Wadi, numbered from one to five from head to tail. Wadi Zabid bifurcates just upstream of Weir #4 into Wadi Nassery and Wadi Ain. Water is diverted from the primary canals to the secondary and then to the tertiary canal outlets using temporary earth bunds. The outlets generally comprise gated pipe orifices that extend under the feeder canal embankments. The canal system in Zabid is not modernized and no cross regulators are available at present, so farmers build earth bunds to divert flood water to the field turnouts along the canals. Water is then distributed from field to field in a traditional manner.

The main crops grown in Wadi Zabid are fruits (mainly banana, mango and citrus), sorghum for grain and for fodder, cotton, vegetables (onion, tomato, okra, etc.), sesame and maize.

Flood water is the main source of irrigation water in Wadi Zabid. Nonetheless, the use of groundwater for supplemental irrigation, especially for cash crops such as banana, is on the increase. The unregulated use of the groundwater leads to rapid decline in the water table.

For the purpose of allocating spate water to the command areas of Wadi Zabid, the command areas are divided into three main groups. Allocation to the groups follows the following fixed calendar:

– Group 1: comprising the areas served by diversion structures #1 and #2 (4325 ha) is entitled to take water from Oct. 19 to Aug. 2 (288 days);
– Group 2: comprising the areas served by diversion structures #3 and #4 (9165 ha) is entitled to take water from Aug. 3 to Sep. 13 (42 days); and
– Group 3: comprising the areas served by diversion structure #5 (1725 ha) is entitled to take water from Sep. 14 to Oct. 18 (35 days).

Below the main diversion structures, water is allocated to the outlets in turn from head to tail.

4.5.2 Model description

The SMM model of Wadi Zabid covers the Wadi delta downstream from Kolah gauging station. It comprises the main Zabid Wadi and its branches (Wadi Nassery and Wadi Ain), the main *oqmas* (free offtakes from the wadi), and the canal network down to the secondary level. The total command area for each canal is modelled by three command areas representing the head, middle and tail areas. The modelled command areas of the secondary canals include the areas irrigated from lower-level canals (since those canals are not included in the modelled network).

Average monthly reference evapotranspiration (ETo) for Wadi Zabid area was calculated from available climate data using the FAO CropWat model (CLARKE et al., 1998). Daily rainfall data from two stations (Jirbah and Zabid) for a year with average rainfall was used in the model. Due to lack of real flood flow data for most of the wadis in Yemen, the hydrographs of Wadi Zabid floods (inflow data) were

generated using the FloodSim model (a hydrological model developed specifically for the wadis in Yemen; Working Paper 25, 2003) as depicted in Figure 2. The cropping patterns used in the model were based on quick field surveys. Two cropping patterns were used for the whole wadi area, one for Group 1 command areas and the second for Groups 2 & 3 command areas. Crop data was taken from FAO (1998).

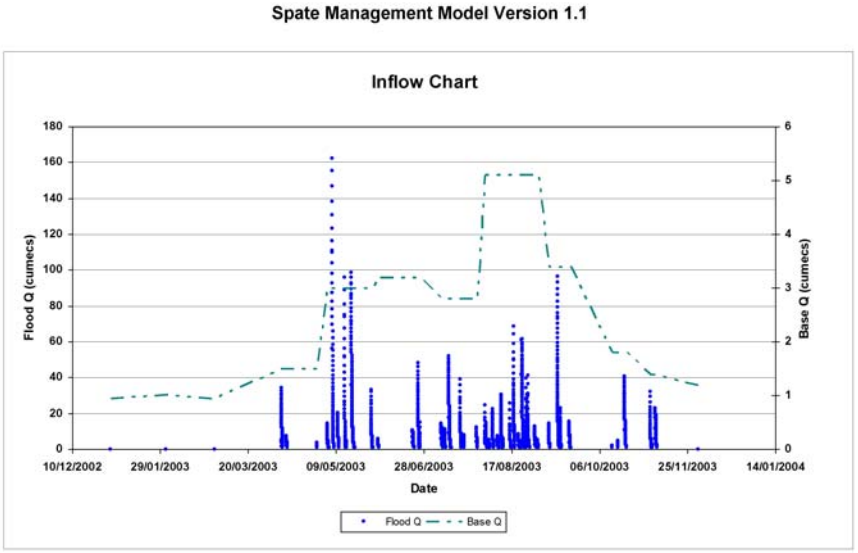

Figure 2:
Flood flow used in the case study

Canal capacities and water rights were based on design and field data. The formulas and parameters defining bed losses from the wadi and canals were taken from LAWRENCE and HINTON (1986). The maximum diversion capacities for the command areas were calculated by assuming that the outlets deliver a water duty of 60 l/s/ha, i.e.: Maximum command area discharge (m^3/s) = area (ha) * 60 (l/s) / 1000

4.5.3 Simulation scenarios

Two runs were carried out using the prepared Wadi Zabid model simulating two water management scenarios:

– Scenario #1 simulated spate irrigation practices, i.e. the SMM was set up to apply fixed-depth irrigation applications to the crops. Usually, a single irrigation is applied to each field before planting; however, more applications may also be given when water is available.

– Scenario #2 simulated optimal irrigation practices, i.e. the SMM was set up to irrigate the crops according to their crop water requirements, taken into consideration water availability and water allocation rules.

Apart from these differences, the remaining simulation parameters were identical for the two scenarios. Accordingly, the results can be used to assess the impact of the two water management scenarios on resource use and project production. The simulation period for the runs was one year from 1/1/2003 till 31/12/2003. Discussion of selected simulation results is presented below.

4.5.4 Results discussion

The output from SMM includes detailed results for each command area as well as summary results for the whole simulated scheme (Wadi Zabid in this case study). The selected summary results presented in Table 1 show that the cropping intensity, and hence the actual cropped area, in scenario #2 was about 3.4 times that in scenario #1. The average potential yield from the cropped area in scenario #2 was 1.9 times that in scenario #1. Combining the results of the cropped area and average potential yield from the cropped area indicates that the total potential crop yield in scenario #2 was expected to be some 6.46 (3.4 * 1.9) times that in scenario #1. Since in the simulations the crops were only grown when sufficient spate water was available at planting time, the cropping intensities and potential crop yields can be used as proxies to water availability.

Table 1:
Selected summary results for simulation scenarios #1 & #2

	Scenario #1	**Scenario #2**	**Ratio 2/1**
Flood Water Use:			
• Water diverted to command areas(1)	35.6%	22.4%	0.63
• Network seepage losses(1)	20.8%	15.5%	0.75
• Outflow(1)	43.6%	62.1%	1.42
Cropping intensity(2)	9.8%	33.4%	3.4
Average field application efficiency	19.3%	77.7%	4.0
Potential crop yield	32.3%	62.7%	1.94

(1) Percentage from the total volume of flood water, which is identical in the two scenarios.
(2) Percentage of the areas cultivated to the total command areas.

Despite of the low cropping intensity in scenario #1, the volume of water diverted to the command areas for irrigation was larger than that in scenario #2. This typically leads to a very low average application efficiency of 19% in scenario #1 compared

to a much higher efficiency of 77% in scenario #2. Because less water was diverted to the command areas in scenario #2, the network seepage losses were also lower. The balance, or the outflow, was therefore larger in scenario #2 than in scenario #1. However, the outflow should not be considered as lost water as it can be used to recharge the groundwater for example.

With respect to the spatial variation in command-area simulation results, the two simulated scenarios depict large differences. For instance, the average cropping intensities in scenario #1 were about 30%, 2% and 0% for the command areas in Groups 1, 2 and 3 respectively with the majority of the areas growing no crops at all (due to water shortage). For scenario #2 the average cropping intensities were higher at about 62%, 25% and 5% for the command areas in Groups 1, 2 and 3 respectively. Similarly, the average potential crop yields as simulated in scenario #1 were about 18%, 8% and 5% for the command areas in Groups 1, 2 and 3 respectively. For scenario #2 the average potential crop yields were higher at about 66%, 47% and 9% for the command areas in Groups 1, 2 and 3 respectively. These results indicate large differences between the command area groups in the Wadi. Typically, the head group (#1) was advantageous over the middle (#2) and tail (#3) groups.

Note: Some of the Spate Management Model simulation results can be linked to geographic information systems for graphical presentation of spatial data.

The above results indicate that generally scenario #2 outperformed scenario #1. The upstream command areas were better off than the downstream areas in both scenarios. However, the inequity of water distribution and the associated social inequity among the farmers were more pronounced in scenario #1 than in scenario #2. Substantial improvement in water and land resource utilisation can therefore be achieved by adapting the irrigation practices simulated in scenario #2. Nonetheless, there is still room for improvement by introducing further interventions. For instance, the cropping intensity was very low in the two simulated scenarios while in the mean time there were large volumes of unutilised surface water (outflow). This is due to the rigid water allocation rules in Wadi Zabid. These rules may be revised in order to achieve more equitable distribution of the food water and increase water resources utilisation. The SMM makes it possible to test the efficiency of any intervention before recommending it to the farmers.

5. Conclusions

Spate irrigation is perhaps the oldest water management and surface irrigation system in the world. Despite of its nature of high risks and uncertainty, spate irrigation is still being practiced in various parts of the world as an indigenous irrigation method. However, as the shortage of water resources escalates in many irrigated areas; better

management of the valuable water resources is paramount for improving resource utilisation in spate irrigation schemes.

The Spate Management Model (SMM) was developed for the purpose of simulating spate irrigation practices in the flood wadis of Yemen, but could also be applied to spate irrigation schemes in other parts of the world. The model can be used as an aid to decision making in the improved operation and management procedures planned for the wadis. It could also be used to explore the scope for changes to water allocation procedures in order to achieve better water management. Using the model to simulate different water management scenarios for a real-world case study proved its usefulness in this respect.

Currently, the SMM cannot directly simulate the conjunctive use of flood and ground water resources in spate irrigation schemes. On the other hand, such conjunctive use of water resources is on the increase in many spate irrigation areas. Accordingly, it is recommended that the model be developed further to include such a capability.

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