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MODERNIZATION OF SPATE IRRIGATED AGRICULTURE: A NEW APPROACH†

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ABSTRACT

Spate irrigation, a floodwater harvesting and management system, has for the past 70 centuries provided a livelihood for about 13 million resource-poor people in some 20 countries. Despite being the oldest, the system still remains the least studied and the least understood. It is only in the past two decades that the system has been subject to some modernization interventions, much of which focused on improving floodwater diversion efficiency. Effective floodwater diversion measures are necessary, but they must be supplemented with equally effective field water management and soil moisture conservation measures if sustainable improvement of land and water productivity is to be achieved.

This paper draws on studies conducted in the past 5 years, particularly in the Republic of Yemen, Pakistan and Eritrea. The studies employed both qualitative and quantitative methods and assessed the modernization package that could result in lasting enhancement of crop productivity in spate irrigated agriculture. The suggested modernization measures include: avoid overstretching the command area; limit the number of irrigation turns to two or an irrigation gift of 1000 mm; avoid field bund heights of more than 1 m; adopt a field-to-field water distribution system instead of an individual field water distribution system; opt for water rights and rules that entitle downstream fields to the more frequent small and medium floods thereby ensuring equity in both water quality and quantity; optimize soil water-holding capacity and infiltration rate through pre-and-post irrigation tillage, combined tillage as well as soil mulching. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: field water management; modernization; spate irrigation; soil moisture

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RÉSUMÉ

L'irrigation de décrue, un système de collecte et de gestion de l'eau, a depuis 70 siècles procuré les moyens de subsistance à environ 13 millions de personnes pauvres en ressources dans quelque 20 pays. Bien qu'il soit le plus ancien, ce système reste le moins étudié et le moins compris. C'est seulement au cours des deux dernières décennies que le système a fait l'objet de quelques interventions de modernisation, dont beaucoup ont été axées sur l'amélioration de l'efficacité de la dérivation de l'eau. Des actions pour améliorer l'efficacité de la dérivation de l'eau sont nécessaires, mais elles doivent être complétées par des actions concernant la gestion de l'eau au champ et la conservation de l'humidité du sol, si l'amélioration durable de la productivité des terres et de l'eau est visée.

Cet article s'appuie sur des études menées au cours des 5 dernières années en particulier dans la République du Yémen, au Pakistan et en Érythrée. Les études ont employé des méthodes qualitatives et quantitatives et ont évalué le paquet d'actions de modernisation qui pourrait conduire à l'amélioration durable de la productivité agricole des cultures de décrue. Les actions de modernisation proposées sont les suivantes: éviter une surface irriguée excessive; limiter le nombre de tours d'irrigation à deux ou à un seul de 1000 mm; éviter les hauteurs de diguette supérieures à 1 m; adopter une distribution de l'eau d'une parcelle à l'autre au lieu d'une distribution à chaque parcelle; opter pour des droits d'eau et des règles qui autorisent les parcelles de l'aval à bénéficier des crues petites et moyennes les plus fréquentes assurant ainsi l'équité à la fois sur la quantité et la qualité de l'eau; optimiser la capacité de rétention d'eau et minimiser les pertes par infiltration par un de travail du sol pré- et post-irrigation et combiner labour et paillage. Copyright © 2010 John Wiley & Sons, Ltd.

MOTS CLÉS: gestion de l'eau au champ; modernisation; irrigation de décrue; humidité du sol

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INTRODUCTION

Spate irrigation is a type of irrigation system whereby floodwater travelling through normally dry wadis is conveyed to irrigable fields. Spate irrigation floodwater is characterized by discrete events which flow for only a few hours, displaying appreciable discharges and recession flows which last for only one to a few days. The flow is diverted from the wadi channel into typically short steep canals that convey flow to bunded basins, which can be inundated to depths of 0.2–2 m (Mehari *et al*., 2008).

Spate irrigation has existed for the past 70 centuries as a major source of livelihood of mainly economically disadvantaged communities in arid and semi-arid regions. Despite being one of the oldest water resource management systems, it is still the least studied and the least understood and documented. Most investments have been channelled into perennial irrigation systems as these have relatively reliable water sources and are perceived to have a higher sustainable return, and lesser risks and uncertainties with regard to crop and livestock production. That said, there has, in the last two decades, been an increasingly emerging recognition among governments, non-governmental agencies and the donor community that spate irrigation is one of the main assets for bettering the lives of poor communities and is hence worthwhile investing in. This renewed interest has, nonetheless, mainly focused on technical modernization interventions tailored at improving floodwater diversion efficiency.

Apart from improving floodwater diversion efficiency, modernization needs to include a package of field water distribution and soil moisture conservation measures if a sustainable increase in land and water productivity is to be attained. Spate irrigation systems largely operate under water scarcity conditions as they rely on floodwater that is unpredictable in occurrence, duration and volume. Moreover, in several systems, the floodwater precedes the crop production period, making appropriate field water management and soil moisture conservation measures necessary to improve the possibility that a large portion of diverted floodwater is retained within the root-zone depth of the soil profile and made accessible for crop growth.

The efficacy of field water management and soil moisture conservation is affected by several factors, namely the nature and type of field water distribution systems; irrigation turns and gifts; soil water-holding and infiltration capacities; design, operation and maintenance of field bunds; water-sharing rights and rules as well as the mode and timing of tillage and mulching practices. The collective impacts of these factors are discussed in this paper with illustrative examples, and recommendations are made as necessary. The discussion is based on the qualitative and quantitative study conducted in the past 5 years in the spate irrigated agriculture in Eritrea, the Wadi Laba spate irrigation systems in particular as well as in the Republic of Yemen, Tihama Plain and in Daraban Zam, Pakistan. These spate irrigation systems were mainly farmer-managed with the government providing support to repair and maintain the main system infrastructure. The size of individual fields range from 1 to 2 ha in Eritrea and the Republic of Yemen to 5 ha in Pakistan.

The results and discussion are presented under the following topics:

- optimization of irrigation turns and gifts;
- field bund maintenance and field water distribution;
- soil moisture holding and infiltration capacity maintenance and improvement.

Before discussing these topics, however, the key features of the spate irrigation system are described.

SPATE IRRIGATION SYSTEM

Spate irrigation is a type of floodwater harvesting and management, unique to arid regions bordering highlands (Figure 1). In spite of its potential to significantly contribute to the livelihood improvement of marginally poor communities in fragile ecosystems, it is a largely neglected and forgotten form of resource management (Figure 2).

Spate irrigation is practised in West Asia (Pakistan, Iran and Afghanistan), the Middle East (Yemen, Saudi Arabia), North Africa (Morocco, Algeria and Tunesia) and the Horn of Africa (Ethiopia, Eritrea, Sudan and Somalia) and more sporadically in other parts of Africa, South America and Central Asia. The area under spate irrigation globally is substantial. It forms one of the largest, but also least studied and most neglected water harvesting systems. The most accurate estimate of the area under spate irrigation brings it

Figure 1. Pakistan, Daraban Zam: typical spate irrigation catchment

Figure 2. Tihama, republic of Yemen: neglected spate irrigation system

close to around 2 600 000 ha, but the nature of spate irrigation is such that the acreage varies from year to year depending on rainfall. An overview of the main spate irrigation areas is given in Table I. There are also unquantified areas under spate irrigation not presented in Table I, namely in Afghanistan, Saudi Arabia, Tanzania and Kenya. In addition to these there are largely undocumented spate systems in Central Asia, China (Inner Mongolia) and Latin America, whereby first floods are used to fertilize and soften up the land, to be followed by semi-perennial irrigation supplies.

As indicated, in spate irrigated agriculture, floods are the major sources of irrigation. The floods originate from episodic rainfall in macro-catchments. They are diverted from ephemeral rivers and spread over agricultural land. After the land is inundated crops are sown, sometimes immediately, but often the moisture is stored in the soil profile and used later. The spate irrigation systems support low-value farming systems, usually cereals (sorghum, millet, wheat, barley), oilseeds (mustard, castor, rapeseed), pulses (chickpea, clusterbean), but also cotton, cucurbits, tomatoes, vegetables and tree crops such as date palms in the Tihama Plain, the Republic of Yemen. Besides providing irrigation, spate flows recharge shallow aquifers (especially in river beds), they fill (cattle) ponds and in some areas are used to spread water for tree crops, pasture or forest land.

These water management systems are among the most spectacular and complicated social organizations. They require the local construction of diversion structures that are able to withstand floods and guide flash water over large areas, dissipating its erosive power. This requires strong local cooperation and agreement on how to distribute a common good that is unpredictable and uneven (Figure 3).

Another important characteristic of spate irrigation is that sedimentation is as important as water management. Rivers in spate lift and deposit huge quantities of sediment. As a result there is constant change in bed levels, both in the river system and in the distribution network. This results in frequent changes and adjustments. The severity of sedimentation depends on the sediment load of the ephemeral flows. These sediment loads are related to the rainfall pattern and the geology, morphology and vegetation cover of the catchment. Despite the frequent changes, the mere existence of a functioning spate irrigation system will consolidate an ephemeral river system and prevent it from constant braiding and degradation in extreme weather events. Farmers often actively use the force of the sedimentation and scour processes. They may deepen the head reach of a flood channel in order to attract a larger flood that will further scour out the channel. In other cases farmers may block a flood channel to force the bed level up.

OPTIMIZATION OF IRRIGATION TURNS AND GIFTS

Given the unpredictable nature of floodwater in spate irrigation systems, to have in place fixed irrigation turns is a near impossible task – the irrigation gift usually ranges from 500 to 1000 mm of water depth. A flexible irrigation turn is,

Table I. Estimated areas under spate irrigation

Country	Year	Spate irrigated area (ha)	Source
Algeria	2008	53 000	FAO Aquastat (www.fao.org)
Eritrea	2007	16 000	Mehari (2007)
Ethiopia	2007	140 000	Alemehayu (2008)
Iran	2008	450 000–800 000	Kowsar (2005)
Morocco	2008	79 000	Oudra (2008)
Pakistan	1999	640 000–1 280 000	Ahmad (2008)
Somalia	1984	150 000	FAO Aquastat (www.fao.org)
Sudan	2007	132 000	UNEP (2007)
Tunisia	1991	30 000	FAO Aquastat (www.fao.org)
Republic of Yemen	1999	117 000	World Bank (2000)
Mongolia	1993	27 000	FAO Aquastat (www.fao.org)
Kazakhstan	1993	1 105 0001	FAO Aquastat (www.fao.org)

Figure 3. Sheeb, Eritrea: collective spate flow management and field bund maintenance

however, a common practice. For many centuries, farmers have drafted and implemented a set of water rights and rules that, among other things, direct which field would have to be irrigated first from what flood category. To this end, perhaps the two most important rules have been:

- the water rule on the second, third or fourth turn, which states that a certain field can receive a second, third or fourth turn only after all other fields receive one, two or three turns respectively;
- the water rule with regard to the different flood categories, which allocates small and medium floods (10–50 $m^3 s^{-1}$), and occasionally moderately large floods (50–100 $m^3 s^{-1}$) to the upstream fields; moderately large and sometimes large floods (100–200 $m^3 s^{-1}$) to the midstream fields; large and very large floods ($> 200 m^3 s^{-1}$) to the downstream fields.

At the core of the water rules is ''fairness'', which is the underlining water-sharing principle in many spate irrigation systems. The enforcement of the rules and the attainment of fairness between upstream and downstream users have, however, been formidable tasks. This is largely because farmers believe that three irrigation turns (1500 mm) or more result in twice as much yield as two irrigation turns (1000 mm) and they strive to secure at least three turns at the earliest period possible during the flood season (Mehari et al., 2005a). This, on several occasions, has led to violation of the water rules. While such violations have been relatively limited in indigenous spate irrigation systems where earthen and brushwood structures known as *agims* and *musghas* divert and distribute the floodwater, they have been more pronounced in the modernized spate irrigation systems which utilize concrete headwork diversion structures. Medium and larger floods have frequently destroyed the indigenous structures, thereby increasing the likelihood of safeguarding the rights of the midstream and downstream fields to the large floods. The frequent failure of the structures also meant that the upstream farmers had to depend on the midstream and downstream farmers for timely maintenance. This interdependence has served as a catalyst in forcing the upstream farmers to, in most cases, let the large floods pass through their fields to the downstream area. Following the infrastructure modernization in the 1970s and 1980s in Yemen and Pakistan and in 2000 in Eritrea, which replaced the *agims* and *musghas* with a stronger concrete headwork, the frequency of failure of the main structures has been significantly reduced and with it the interdependence among the farmers for timely maintenance. As a result, upstream farmers have frequently used large floods and violated the rule of turns.

The central argument being made in the above is that the belief that three or more irrigation turns can result in higher yields has significantly contributed to violations of water rules and deprivation of some midstream and particularly downstream fields of their entitlement to irrigation turns and large floods. Consequently, the amount of water supplied to some fields has not been sufficient to enable the retention of net soil moisture required for optimum yield of the major crops in spate irrigation systems. But given the fact that soils have limited infiltration rates and water-holding capacities, is it necessarily true that more than two irrigation turns will significantly increase crop yield? This central question was addressed in the study conducted by the authors on silt loam and sandy loam soils in the spate irrigated fields in Eritrea (Mehari, 2007). These are the dominant soils in the spate irrigated fields in Pakistan and Yemen.

The study assessed the amount of the soil moisture retained by a spate irrigated field in Wadi Laba, Eritrea, at the start of the growing period under three different irrigation turn scenarios and about 45 irrigation turn combinations. The scenarios were:

- *highly likely scenario*: a field receives two irrigation turns in July and a third in either June or August, on a bi-weekly interval between any two turns;
- *less likely scenario*: a field is irrigated twice in either June or August and once in July at an interval of 15 days between any two irrigations;
- *unlikely, yet possible scenario*: a field gets two or three irrigations in June or August at a weekly interval between any two supplies.

These scenarios are based on the fact that in Wadi Laba (Eritrea) as is the case in many spate irrigated areas in Pakistan and Yemen, 15 June to 15 August is the effective flood season; July is the month when at least 50% of the total annual number of floods occurs; and very rarely does a field get a second turn before a two-week interval. The irrigation turn scenarios and combinations are presented in Table II.

Table II. Scenarios and irrigation schedule combinations for silt loam soils (Mehari, 2007)

Irrigation schedule scenarios and combinations	Flood months						
	June		July			August	
	15	30	1	15	30	1	15
Highly likely scenario							
Three irrigation turns	*I*		*I*	*I*			
	I			*I*	*I*		
	I		*I*		*I*		
		I		*I*	*I*		
	I		*I*			*I*	
	I		*I*				*I*
	I			*I*		*I*	
	I			*I*			*I*
	I				*I*		*I*
		I		*I*		*I*	
		I		*I*			*I*
		I			*I*		*I*
			I	*I*		*I*	
			I	*I*			*I*
			I		*I*		*I*
				I	*I*		*I*
Two irrigation turns	*I*		*I*				
	I			*I*			
	I				*I*		
	I					*I*	
	I						*I*
		I		*I*			
		I			*I*		
		I				*I*	
		I					*I*
			I	*I*			
			I		*I*		
			I			*I*	
			I				*I*
				I	*I*		
				I		*I*	
				I			*I*
					I		*I*
Less likely scenario							
Three irrigation turns	*I*	*I*		*I*			
	I	*I*			*I*		
	I	*I*				*I*	
	I	*I*					*I*
			I	*I*	*I*		
			I			*I*	*I*
				I		*I*	*I*
Two irrigation turns	*I*	*I*				*I*	*I*
Unlikely, yet possible scenario							
	15	22	30		1	7	15
Three irrigation turns	*I*	*I*	*I*				
					I	*I*	*I*
Two irrigation turns	*I*	*I*					
					I	*I*	
		I	*I*				
						I	*I*

Source: Note: I = one irrigation turn with a 50 cm gift.

The soil moisture storage analyses were done using the spate irrigation tailored simple spreadsheet-based Soil Water Accounting Model (SWAM) (Mehari, 2007) and the results were validated with the more complex well-established Soil Water Atmosphere Plant (SWAP) model (Kroes and Van Dam, 2003). The summary of the soil moisture simulation results obtained from both models is presented in Table III.

The following inferences can be drawn on the basis of Table III:

- there is no difference between the amount of soil moisture stored in the root zones of sorghum and maize, the major spate irrigated crops, at the onset of the planting season, regardless of whether a field receives two (1000 mm) or three irrigation turns (1500 mm) as long as the date of the last irrigation turn remains the same;
- a field irrigated twice (irrigation gift is 50 cm each time) can retain 730 mm of soil moisture at the start of the planting season if the last irrigation turn is received by the end of July. Providing a third turn of 50 cm to an upstream field that has secured its second turn by the end of July would only increase its soil moisture depth by about 5 cm from 73 to 78 cm – about 90% of the applied water would be lost.

The models also showed that:

- a fourth irrigation turn is wasteful regardless of when it is applied during the effective irrigation period (from 15 June to 15 August); it does not increase the net soil moisture storage beyond 78 cm;
- a single irrigation turn of 50 cm will put sorghum and maize crops, particularly the ratoon, under water stress as it at best results in net soil moisture storage of about 40 cm, which under the climatic conditions in the spate irrigated systems in Eritrea, the Republic of Yemen and Pakistan, is just sufficient for the seeded crops.

These findings lead to the following interventions that could help improve water use efficiency and distribution uniformity:

- limiting the number of irrigation turns to a maximum of two or capping the gross water depth application at 1000 mm for irrigated fields with silt loam and sandy loam soils. This would enable water saving mainly in the upstream fields of a maximum of 500 mm, which could be made available to the midstream and downstream areas;
- modifying the earlier stated water right on flood sizes to read: regardless of the size of the flood, if the upstream and/or the midstream fields receive two or three turns by mid or the end of July, the subsequent floodwater would have to be conveyed to the downstream fields. This implementation of the modified water rule may not be met with stiff resistance, as it simply paves the way for the

Table III. Soil moisture storage simulation with the SWAM and SWAP models at the onset of the planting period (mid September) for spate irrigated fields with silt loam and sandy loam soil profiles (Mehari, 2007)

Irrigation schedule scenarios	Possible irrigation interval combinations based on the time of the last irrigation turn		Soil moisture within the 2 m deep root zone of sorghum and maize (cm)	
	Day last irrigation turn received	No. of interval combinations	SWAM model	SWAP model
Likely scenario				
Three turns	15 July	1	67	69
	30 July/1 August	7	72	73
	15 August	8	77.5	77
Two turns	I July	1	62	66
	15 July	3	66	69
	30 July/1 August	8	71	72
	15 August	5	77	77
Less likely scenario				
Three turns	15 July	1	67	69
	30 July/1 August	3	72	72
	15 August	3	77.5	77
Two turns	30 June/1 July	1	62	66
	15 August	1	77	77
Unlikely scenario				
Three turns	30 June/1 July	1	62	66
	15 August	1	78	77
Two turns	22 June	1	60	65
	30 June	1	62	66
	7 August	1	74	74
	15 August	1	77	77

enforcement of the overriding rule on irrigation turns. The modified water rule could have twofold advantages:

* it increases the amount of water supplied to the whole irrigation system in general and the downstream fields in particular. Small and medium floods account for as much as 50% of the total number of floods that occur in a given flood season (Mehari *et al*., 2005b);
* it improves the uniformity distribution of floodwater quality among the upstream and downstream fields. Mehari (2007) has found that large Wadi Laba floods in Eritrea were moderately saline with a potential to reduce the yield of sorghum and maize by 30 and 50% respectively. Whereas small and medium floods were non- saline.

FIELD BUND MAINTENANCE AND FIELD WATER DISTRIBUTION

Unassuming as they may seem, field bunds are a major determining factor regulating soil moisture in spate irrigated fields. As such field bunds and the way they are maintained have a profound impact on water productivity from spate irrigation. Their importance can be derived from their central place in some of the management arrangements in spate systems. In the rules and regulation for the Wadi Laba spate irrigation system in Eritrea and the Wadi Tuban spate irrigation system in Yemen, there have been explicit penalties for farmers who do not take sufficient care in maintaining the field bunds; they can include compensating for the crop loss of a disadvantaged neighbour. Further steps are the hereditary tenancy arrangements that are common in Pakistan's spate irrigation systems. Under these arrangements the hereditary tenant is the de facto co-owner of the land, but his entitlement is tantamount to his continued upkeep of field bunds. The word for a hereditary tenant, *lathband*, in fact means ''the one who maintains the field bunds''. Maintaining field bunds is an individual responsibility with a collective impact, because if bunds in one field are neglected, the water will move across the command area in an uncontrolled fashion, not serving large parts of it and causing field erosion at the same time. It is best to look at the system of fields and field bunds as a single fabric that suffers when damaged.

Field bunds across spate systems differ widely – in particular in height. In Yandefero in South Ethiopia field bunds are 20 cm high – not different from field bunds in perennial systems. In Wadi Laba in Eritrea, field bunds differ in height between 50 cm and 1 m. In Daraban Zam in Pakistan they can be up to 3 m. The main factor is the number of floods that a field may be expected to receive. In Yandefero the command area was served by a succession of mild floods. In Wadi Laba and Yemen a field may receive two or three floods, but in Pakistan where the fields are very large (sometimes in excess of 5 ha), a single watering system is practised.

Short field bunds of 20 cm in height may be desirable for the fact that they would require less labour and material resources to (re)construct and maintain, but they may be a reason that a certain field does not receive sufficient irrigation water. Given the unpredictable nature of the floodwater, the major source of irrigation in many spate irrigation systems, most fields may rarely be irrigated more than twice. As indicated in the earlier section for silt loam and sandy loam soils, and these have very high water-holding capacities (35 mm m^{-1}, De Laat, 2002), a gross application of 1000 mm would be needed for a field to retain a net soil moisture of 700–750 mm and provide an optimum yield of the commonly spate irrigated crops such as sorghum and maize.

Very high field bunds of 1–3 m pose a great challenge for timely repair and maintenance, particularly when machinery is not to hand and traditional labour and oxen-driven *mejhaf*, a flat metal plate designed to scoop large quantities of soil, are the only available resources (Figure 4). While 2–3 m high field bunds are common in many large (5 ha or more) spate irrigated fields in Pakistan and Yemen, having a field bund of more than 1 m may not have a practical value even in systems where one irrigation turn is the rule. Soil water simulations have shown that for silt loam and sandy loam soils, a single irrigation turn of 1000 mm can result in a net soil moisture equivalent to that obtained from two irrigation turns of 500 mm each, provided the timing of the last irrigation turn is the same. Thus, a single watering of 1000 mm could sufficiently support the said optimum yield of sorghum and maize. It is remarkable to note here that several downstream fields in Pakistan with bund heights of more than 1 m are not being drained in a timely manner to

Figure 4. Wadi Laba, Eritrea: field bund maintenance with oxen-driven *mejhaf*

allow proper land preparation for crop growth to take place from mid September to April when the local climatic conditions are conducive. Given the field-to-field water distribution system, the finest silt loam sediments with the lowest infiltration rates accumulate in the downstream fields, resulting in prolonged periods when water remains standing on the surface.

It is not only the height of the bunds that matter but also their strength. Poorly (re)constructed and maintained weak bunds may break prematurely and irrigation water may be lost with it. The strength of a bund is also of great concern to neighbouring farmers. Bunds that may break in an uncontrolled manner will all of a sudden release a large quantity of water to one's field. Particularly if there is a level difference between two fields such a sudden release may create gullies, which unless properly plugged (and this is expensive), can cause floods to quickly disappear from the concerned irrigated area and soil moisture will be significantly reduced.

Controlled overflow hence is a major concern, particularly in a field-to-field water distribution system. Apart from giving field bunds a minimum strength, a number of other techniques can be adapted to control field-to-field overflow:

- keeping the bunds at the same level so that water can overflow over a relatively large stretch;
- making a shallow ditch immediately downstream of the field bund to spread the overflowing water over the entire breadth of the downstream field. This is done in Pakistan, where field bunds are very high;
- reinforced overflow structures usually with local stone pitching to make sure water starts to overflow gradually without unpredictable breaking of the field bund. These are common in Yemen (Figure 5), particularly in areas with armoured river beds, where there is an ample supply of stones. In Pakistan a field overflow structure has been developed by the Water Resource Research Institute that consists of an orifice with a round lid to close it. Downstream of it is a small stilling basin that ensures the energy of the overflow is dissipated and water spreads generally over the downstream field. This innovative structure (Figure 6) has gained quick popularity in the area where it was introduced.

Besides the need to control overflow, the choice between field-to-field and individual field water distribution systems would also have to be made based on the coherence of the system with the nature and type of the floods and the existing water-sharing rules. For instance, the modified water rule discussed above cannot ensure that small and medium floods reach the furthest midstream and downstream fields under a field-to-field water distribution system. This system significantly reduces the already low energy and flow velocity of the floods. A complete shift to an individual field water distribution supplied with small canals may also not be a better option because:

1. Small canals and field inlets do not allow large volumes of water to be applied to fields rapidly in the short period of time that spate floods occur. As can be seen from Figure 7, spate flows are characterized by a short duration peak followed by a sharp decline in discharge and a long recession period that extends from several hours to 3–4 days (Mehari *et al*., 2005b);
2. The need for several canals reduces the irrigated command area by as much as 25%.

Therefore, the best alternatives that would have to be considered are:

- adopt a field-to-field water distribution system but significantly reduce the size of the command area under one intake. In some spate irrigation systems in Eritrea and Yemen, as much as 100–200 ha are supplied via a single intake. These area could be divided into five blocks of 20–40 ha each;

Figure 5. Tihama, Yemen: stone-pitch overflow control structure

Figure 6. Pakistan: orifice with a stilling basin

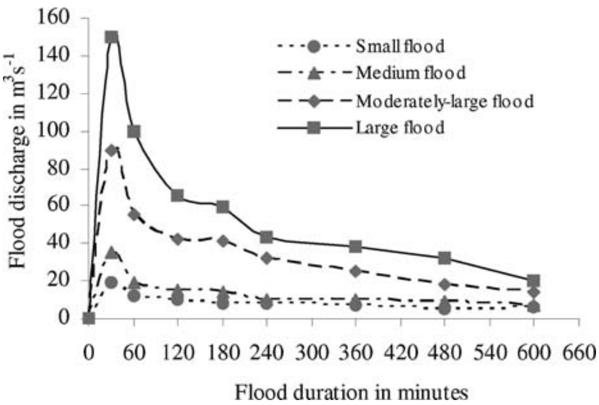

Figure 7. Flood hydrograph of different flood categories (Mehari *et al.*, 2005a)

Figure 8. Pre-irrigation tillage in Eritrea

- provide separate off-takes to the midstream and downstream fields so that they can directly divert floods from the wadis (ephemeral rivers).

SOIL MOISTURE HOLDING AND INFILTRATION CAPACITY MAINTENANCE AND IMPROVEMENT

If two irrigation turns or 1000 mm of gross irrigation depth is to result in net soil moisture of 700–750 mm and produce an optimum yield of some of the major crops in spate irrigated agriculture, the soil profile must have a good water-holding capacity as well as good infiltration rate. In most spate irrigation systems, the soil profiles are a result of successive alluvial silt loam and sandy loam deposition. These soil profiles have high water-holding capacity at 300–350 mm m^{-1}; their basic infiltration rate (20–25 mm h^{-1}) is categorized as moderately rapid.

These high water-holding capacities and infiltration rates would have to be enhanced or at least maintained if spate irrigation systems are to have high land and water productivity in a sustainable manner. To this end, some practical measures include:

- pre- and post-irrigation tillage;
- soil mulching, *mekemet*;
- combined sowing and ploughing tillage practice.

Pre- and post- irrigation tillage

In pre-irrigation tillage (Figure 8), breaking down the topsoil to increase the infiltration rate is the major objective. Such a practice has increased the infiltration rate in Wadi Laba, Eritrea, from 23 to 30 mm h^{-1}. Pre-irrigation tillage also makes cultivation much easier and quicker to carry out once the floodwaters arrive, which is important as a lot of labour is required to cultivate the land after irrigation.

In post-irrigation tillage (Figure 9), which is commonly called conservation tillage, the topsoil is tilled loosely to break soil crusts and fill large cracks thereby reducing evaporation losses. This tillage practice is done two to three weeks after irrigation. It would have been better if it had been done within the first week after irrigation so as to reduce any soil moisture losses, but it is practically not possible to till the land when it is still wet.

Soil mulching, mekemet

Soil mulching is locally called *mekemet*, a term derived from the local Tigre word *kememnaha*, which literally translated means ‘‘we have sealed it’’. This technique is practised after the conservation tillage in the two-week period between the flood/irrigation and planting time. It can also be done earlier if the field in question is not expected to receive any additional irrigation. During operation, the farmer (operator) stands on the oxen-drawn wooden plate (also called a *mekemet*) and scoops out a thin layer of soil mulching surface soil pores (Figure 10).

Figure 9. Post irrigation (conservation) tillage

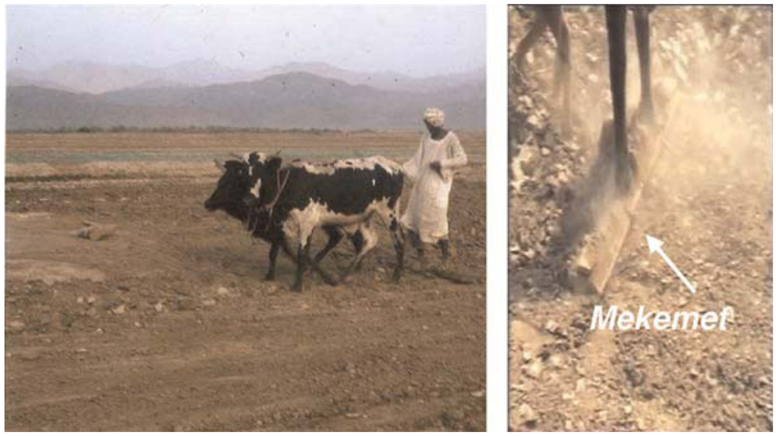

Figure 10. Soil mulching to reduce evaporation losses and increase net soil moisture storage

Combined sowing and tillage practice

Following conservation tillage, spate irrigated fields are usually tilled three to four times during the planting period. The practice that combines ploughing and sowing reduces the number of deep tillages, thus minimizing the degree of compaction of the subsoil and this enhances soil hydraulic conductivity and infiltration rate. This practice, which was invented by the farmers, uses the so-called ''*jeleb*'', a hollow plastic tube into which the plough operator drops two or more seeds every few seconds while tilling the land (Figure 11). The reduction of the degree of compaction due to simultaneous ploughing and sowing is the main reason behind the low soil bulk density in traditional spate irrigation systems, which ranges from 1000 to 1300 kg m ^{3}. A bulk density of 1600 kg m^{3}affects root growth; one of 1800 kg m^{3} severely restricts it.

In the spate irrigated areas in the Eastern Lowlands of Eritrea where the above-discussed soil moisture and conservation measures are practised, the sorghum crop yield was found to be about 4 t ha $^{-1}$. In many spate irrigation systems in Yemen and Pakistan where the said measures are not common, the sorghum yield varies from 1 to 1.5 t ha $^{-1}$ (Van Steenbergen, 1997).

Figure 11. Simultaneous ploughing and sowing

CONCLUSION AND RECOMMENDATIONS

Modernization interventions in spate irrigation have mostly concentrated on improving the diversion of spate flows rather than improving the productivity of irrigation water. In spite of substantial potential gains, there has been little attention towards command area development, improved field water distribution and facilitating moisture conservation. These components have as large or larger impact on crop production than improving water supply. Thus, they would have to be considered as an integral part of spate irrigation modernization efforts.

This paper has recommended several better field water management and soil moisture conservation measures:

- reduce the total irrigation gift from 1500 to 1000 mm. This can be delivered in two turns of 500 mm each as is the case in Eritrea and Yemen; in five turns in spate irrigation systems in Yandefero, South Ethiopia, where floods are frequent and field bund heights rarely exceed 0.2 m, or in one turn of 1000 mm in Pakistan where fields are large with a bund height of up to 3 m. This saves 500 mm ha^{-1} in upstream fields making it available to midstream and downstream areas. A gross irrigation of 1000 mm is sufficient for the optimum yield of maize and sorghum, the major crops in spate irrigated agriculture;
- introduce water rights that allow irrigation of downstream fields with small and medium floods – these floods are currently reserved for upstream and mid-

stream fields. This has twofold advantages: (1) it increases the amount of water supplied to the whole irrigation system in general and the downstream fields in particular. Small and medium floods account for as much as 50% of the total number of floods that occur in a given flood season; and (2) it minimizes salinity build-up in downstream fields. Large floods that are commonly allocated to downstream fields are usually more saline than small and medium floods;
- adopt a field-to-field water distribution system but significantly reduce the size of the command area under one intake and one canal. In some spate irrigation systems in Eritrea and Yemen, as much as 100–200 ha are supplied via a single intake. This area could be divided into five blocks of 20–40 ha. A field-to-field water distribution, unlike individual field water distribution, allows large volumes of water to be applied to fields rapidly in the short period of time that spate floods occur. To reduce damage to field bunds due to application of a large quantity of floodwater, overflow structures such as simple stone pitched and concrete orifices with stilling basins would have to be introduced;
- limit field bund height to 1 m. As indicated, a single irrigation gift of 1000 mm is sufficient for optimum crop production. Also 2–3 m high field bunds result in prolonged periods when water remains standing on the surface, thus impeding timely land preparation and tillage practices. Such unnecessarily high field bunds are also difficult to maintain. If bunds in one field are neglected, the water will move across the command area in an uncontrolled fashion, not serving large parts of it and causing field erosion at the same time;
- introduce better soil moisture conservation practices such as pre-irrigation, conservation and combined tillage as well as soil mulching. These practices have improved soil moisture conservation and increased sorghum yield in Eritrea by about 2 t ha^{-1}.

It has to be noted that this conclusion and recommendations are largely based on sandy loam and silt loam soils; their applicability for other types of soils would have to be checked.

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