Chapter 8

Improving Traditional Spate Irrigation Systems: A Review

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Additional information is available at the end of the chapter

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Abstract

Although the spate irrigation system is an ancient practice, it is only in the past very few decades the system has undergone little modernization interventions. However, these interventions were mostly in the aspects of heavy investment in the sophisticated head works for improving flood water diversion efficiency. In many cases, the modernization interventions were not successful due to various problems such as heavy sedimentation, high flood, disturbed local water distribution rules, or the new designs were not coherent with home-grown practices. On the other hand, successful improvements incorporate less labor intensive and relatively permanent structures with the advantages of conventional systems without considerably altering the approach of the spate irrigation practice. Thus, in this chapter, the techniques of improving traditional spate irrigation systems were reviewed. Farmer-implemented improved traditional spate irrigation systems: flow diversions; canals and control structures; management of sediment, field water, and soil moisture and agronomic practices; reactive water rights and distribution rules were assessed. Therefore, this chapter helps as a reference material for teaching, training and research activities, and it plays a great role in the efforts of sustainable spate irrigation systems development, rehabilitation and management programs.

Keywords: bed bars, flood diversion, intakes, sedimentation, soil moisture, water rights

1. Introduction

Spate irrigation is being practiced in dry-land regions for food security and livelihood improvement. Spate irrigation was defined by [1] as "a resource system, whereby flood water is released through generally dry wadis (ephemeral streams or seasonal rivers) and transmitted to irrigable fields." According to Ref. [2], spate irrigation is a scheme redirecting flash floods from the river bed using conveyance structures (canals) to bunded fields situated at a certain distance from the water source.

The broad definition of the spate irrigation system as provided by [3] is "an ancient irrigation practice that involves the diversion of flashy spate floods running off from mountainous catchments where flood flows are channelled through short steep canals to bunded basins, which are flooded to a certain depth." According to Ref. [3], floods are usually flowing for only a few hours with substantial discharges and with recession flows lasting for only one to a few days. The spate irrigation depth could range from 0.2 to 2 m [4]. Subsistence crops, regularly sorghum, are cultivated using moisture stored in deep alluvial soils after one or more spate irrigation [5].

Flash flood irrigation has been practiced since 70 centuries ago as a main means of survival and income source for the poor in dry-lands [6]. It is being practiced in Latin America, Central and West Asia, the Near East, North and the Horn of Africa [5]. Even though spate irrigation is an ancient practice, it is still the least documented, understood and studied [6]. As a result, no exact data are available for the global spate irrigated area. However, the estimation is about 2.0–2.5 million hectares (10^6 ha) by [7] and 2.6×10^6 ha by [6].

The estimation has become difficult because the spate irrigation has no much consideration by development organizations as that of irrigation from permanent water sources, and the change of spate irrigated area from time to time [6, 8]. In many countries, the spate irrigated area is stable, in North Africa declining, but rapidly expanding in the Horn of Africa, especially in Ethiopia and Eritrea due to settlement in large low land areas [5]. However, there is huge spate irrigation potential globally [7].

Spate irrigation has many advantages in dry-lands. For example, a study conducted by [9] showed a significant increase of barely yield under spate irrigation in Gareh-Bygone plain, Iran. The short duration floods diverted from the dry wadis could be used to irrigate pasture/forest land, recharge groundwater, fill drinking water ponds for human beings/livestock, control flood and conserve biodiversity [5, 10].

According to Ref. [11], flood water spreading in Gareh-Bygone plain (Iran) facilitated spate irrigation of rangeland and groundwater recharge. This reversed migration of communities who have left the area due to groundwater depletion. An artificial recharge of the course grain alluvium area in Iran is a rational option to building large dams. Spate irrigation contributed groundwater recharge and mitigated agricultural drought in Tunisia [12].

Even though spate irrigation has a number of benefits, it is prone to high risks and uncertainties such as too little or no flood water, structural damage by exceptionally large floods and sedimentation of canals and fields [13]. Spate irrigation is special from perennial irrigation in several cases as it requires unique approaches and skills that experts are not all the time conscious [5].

However, the spate irrigation system has been the subject to inappropriate modernization interventions on head works, canals and distribution structures. These interventions, in many cases, were not successful [4, 14, 15]. The modernized spate irrigation system was failed to

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irrigate the anticipated area in Wadi Laba, Eritrea, due to improper approaches and design assumptions used in modernization, the modern designs disturbed the home-grown water allocations and rules, culvert sedimentation, wrong use of scouring sluice and breakdown of breaching bunds [4]. According to Ref. [16], improving spate irrigation effectiveness by the modernization of the distribution and diversion structures of Makanya catchment spate irrigation system (Tanzania) is not feasible because of high sedimentation. As an alternative, investment in the conjunctive use of groundwater was suggested by [16] as it employs little involvement, minimizes the scheme disruption, and hence it maintains the existing water management rules.

From experience, the best successful improvements incorporate less labor intensive and relatively permanent structures with the advantages of conventional systems without considerably altering the existing approach of the spate irrigation practice [2, 5]. Hence, slight improvements to conventional structures with minimum modifications to locally used canals and water rights are ideal [2]. In general, to improve the traditional systems, the technology adopted should be easy for construction and friendly for maintenance, and the materials used must be inexpensive and locally available.

Therefore, the objective of this chapter is to examine techniques of improving traditional spate irrigation systems. The existing gaps in spate irrigation systems were reviewed, summarized and suggested for improvement. This strengthens any sustainable spate irrigation system development, rehabilitation and management efforts aimed at improving food security and livelihood in water-scarce environments.

2. Classification of spate irrigation systems

The three types of spate irrigation systems based on infrastructure are traditional intakes and canals, improved traditional systems, and modernized systems [5].

2.1. Traditional intakes and canals

The two types of traditional intakes are spur-type deflection and bunds that are constructed crosswise the flood channel in flatter plain areas. The construction of diversion is uncomplicated and temporary. Pictures and more explanation for these intakes are available in Ref. [5]. Traditional intakes use only local materials and indigenous skills and might have made possible irrigation to be continued for several years [17]. The location and layout can easily be adjusted to suit the changing wadi conditions as traditional intakes are very flexible and low cost.

On the other hand, the major drawbacks of traditional intakes are their continual requirements of a high amount of labor, and brushwood and tree materials to maintain, reinforce or rebuild intakes that are broken or washed out by huge spates [5]. Hence, the improvement of traditional spate irrigation systems is required to minimize the stated drawbacks.

2.2. Modernized spate irrigation systems

Modernized systems are generally identified for their durable and hard diversion structures built diagonally in wadis such as a weir, the sluice gate, intake, main canals and retaining walls [14]. Pictures of modernized schemes are available in [2, 14]. Much of these modernization interventions seen in the last three decades were focused on improving the efficiency of flood diversion [6]. In large schemes, any conventional intakes were replaced with single concrete diversion weirs having sluice gates to remove sediment. In newer schemes, steep canals and sediment control structures are constructed for reducing sedimentation. Nevertheless, increasing diversion efficiency using a single modern/permanent structure at one location can alter the existing distribution and access to spate water between upstream and downstream farmers and causes conflict between them [5, 6].

2.3. Improved traditional systems

Improved traditional spate irrigation systems are farmer-executed upgradings such as spillway and flow throttling arrangements near close to canal heads and flow distribution and drop structures in the main canals [5]. Water regulating structures can also be included in the canal and field systems, simple rubble masonry or gabions can be used for diversion, and in some areas, earth-moving equipment (bulldozer) may be used to construct diversion bunds.

3. Improving spate irrigation systems

3.1. Main challenges to improve spate irrigation systems

As spate irrigation systems are located in remote and forgotten areas where there is deep-rooted poverty, they face substantial problems: absolute lack of support systems; sustainability of systems is susceptible during a series of drought years when framers are forced to migrate; little support to agronomy in spate irrigation with little research and international sharing of experience; inequity described by significant inequality or usually intricate tenure relationships that obscure local collaboration and reasonable water allocation; political or policy invisibility; and inappropriate approaches followed in the past such as modernizations with heavy investments in sophisticated head-works which were no longer functioning in many areas [7].

3.2. Ways to improve spate irrigation systems

Methods of improving spate irrigation systems include: improving the existing traditional diversions, guaranteeing improvements do not affect traditional water distribution rules; avoiding a high flood and sedimentation damages to command area; improving water productivity, and soil moisture management and conservation; improving field preparations, seed treatment, and use of improved seed; early planting and targeted use of agrochemicals; introducing new crops; and an appropriate crop selection for spate irrigation [5–7].

In addition, promoting local agroforestry; improving drinking water facilities in spate areas; improving land and water tenure, issuing individual titles where they do not exist and codifying or reviewing water rights so as to minimize conflicts and accommodate new realities such as intense use of groundwater and the need for recharging; working on the bigger picture: improving access roads to spate-irrigated areas, general amenities and market facilities and integrated water resource management are ways to improve spate irrigation [7].

Improvements to spate irrigation systems must be designed so as to reduce the labor required to maintain intakes, improve the control of water within the distribution systems and minimize the capacity of large floods to damage canals and fields [2, 5, 6]. Their design must ensure that they can cope with frequent and sometimes large changes in river beds; improvements must recognize and respect the established system of water rights, priorities, and amounts. It is not advisable to replace the traditional spate irrigation systems with the modernized ones or to implement the modernized ones in new projects. Hence, improvements in the traditional spate irrigation techniques should be made as it was briefly discussed in the following sections.

4. Improving traditional spate irrigation systems

4.1. Improving traditional spate diversion structure

The three types of improvement to diversion structures are intakes (diversion structures), canals and regulating structures, and wadi (seasonal or Ephemeral River) training structures [5]. There are different types of diversion structures which depend on resources available for construction, farmers' preference, and site conditions. These are more long-lasting diversion spurs with breach/overflow parts; improved diversion bunds including the use of fuse plugs and bed bars; controlling flows admitted to canals including natural orifice control or gated intake structures; rejection spillways; and a combination of the above [5]. A typical layout of improved intake is shown in Ref. [18].

Based on cost and local conditions more durable diversion spurs can be constructed from reinforced concrete, rubble masonry or gabions on a deep foundation [2]. Improved bunds can be constructed using earth moving machines. A more permanent weir has to be designed with overflow section and energy dissipation structures. Pictures for improved traditional bunds: diversion weir with a stepped downstream face and diversion weir with breachable bund are available in [2, 5].

It is also possible to use a concrete-faced traditional weir with improved downstream scour protection, and abutments extended with gabions. The durability of different diversion spurs was evaluated by [19] as shown in **Table 1**. The improved gabion diversion spurs are the most long lasting (durable) as they require less maintenance.

Type of material used for diversion spur	An average number of reconstruction required during a usual spate season
Traditional Wadi bed material and brush-wood	2–4
Stone	0–1
Gabion	Can last up to 5 years
Source: Haile [19].	

Table 1. Durability of traditional and improved gabion diversion spurs in Eritrea.

Gabions are preferable to a concrete wall that could fracture and fail where the ground is liable to subside [20]. Moreover, gabion maintenance is manageable by farmers. Sorghum production showed an incremental of about 100% (from 2000 to 4000 kg/ ha) and 75% (from 2000 to 3500 kg/ha) in Hidmoand Urkudi, and Adiharemli and Wudet areas, respectively in the Aba'ala plains of Ethiopia by improving flood diversions [20].

4.1.1. Intakes

The designs of intakes and gates can be affected by the type and characteristics of spate flows and sediment concentrations. It is advisable to have open intakes rather than the gated ones as the gated intakes are difficult to operate with high floods coming at unexpected hours. For example, wide open intakes as introduced in Ethiopia might be suitable [15]. The farmers' perception for the main cause of the structural failure of modern spate irrigation systems in Raya Valley (Ethiopia) is narrow intake and canals, less angle of intake deflection, and the existence of the sluice gate as many floods can be lost while scouring sediments under the sluice gate [14].

The interventions on intake width and deflection angle can increase irrigated areas. For example, a study conducted by [14] showed that improving the intake deflection angle from 120 to 150° for 3-meter wide intake, the intake width from 3 to 5 m at 120° deflection angle, and the intake width from 3 to 5 m and deflection angle from 120 to 150°, can increase irrigation area by 21, 81, and 100% respectively [14]. However, these interventions in the deflection angle and intake width did not result in any significant reduction of sediment deposition at the intake. An intake with 5 m wide and 150° deflection angle was suggested from the design point of view; however, a detailed cost–benefit analysis was recommended to be done to make a final decision [14].

An example of the improved entrance to canal formed by two conical stone structures, with a circular base diameter of 3–4 m was shown in [2, 5]. The stone abutments were built by excavating a circular foundation of 2 m deep, lining the abutments with large stones and filling the gaps with smaller stones. The center of abutment structures was filled with small stones and cobbles. The height is usually 2–3 m, and the side slope ranges between 35° and 40°.

4.1.2. Rejection spillways and bed bars

The use of rejection spillways in improved systems is to regulate the flows of floods diverted to canals. It is constructed normally in the first 100 m of the canal, as a side spillway, for easy return of excess water to the wadi (dry river bed) [5]. The spillway depth should be 0.5 m below the canal bank. The spillway section length could vary with many factors such as the geology of the site, the cost of construction, and the degree of safety required. Stones, grasses, and branches can be used to stabilize the spillway sections.

A bed bar is a buried wall with its top at, or slightly above, wadi bed level. It is used to avoid the lowering of the wadi channel adjacent to the canal intake. A mass concrete which can be cast into dug out ditches is the best material for the construction of bed bar [5].

4.2. Improving traditional canals and water control structures

This comprises changes in canal design and the installation of new or improved water control structures. These structures can be grouped into five: check and drop structures, flow-splitting structures, flow spreaders, the field offtakes, and in-field structures. Many of the water control structures used in improved spate irrigation systems are similar to those used in conventional perennial irrigation practice. However, the dimensioning of spate canals does not follow classical irrigation design.

4.2.1. Improving traditional canals

In spate irrigation systems, the objective is to divert the maximum possible amount of water during the very limited duration period of the spate flood to reach as many of the fields as possible. Hence, the discharge capacity per unit irrigated area of intakes and canals of the spate irrigation system must be 10–100 times larger than that for perennial irrigation [5]. When improving or extending spate canal systems, the following points must be taken into consideration: (i) improving existing canal networks can give better water control and overcome some disadvantages of the field-to-field water distribution system, but may require a change in the way that water is distributed; (ii) spate irrigation relies upon water application carried out as quickly as possible; (iii) farmers' prior agreement to proposed changes and their full understanding of the implications for water allocation and distribution are essential for sustainable changes; (iv) where canals are performing reasonably satisfactorily, the design of improved canals should be based on the existing slopes and cross-sections and supported by survey data. Velocities in the canal network should be maintained as close as is possible at a constant level throughout to ensure high sediment-transporting capacity and to minimize deposition in the canals; (v) in flatter areas with alluvial soils, scour damage should be avoided through implementation of regime theory, selection of appropriate canal dimensions and slope, the division of flows and the provision of controlled intakes and embankments and associated bank protection works.

Improved/ remodeled Rod-Kohi conveyance system in Pakistan has increased the reliability of flood water flow, which eventually provided the most favorable moisture level at each diversion point. As a result, the wheat yield (kg/ha) increment was 19–27, 43–62, and 57–68% at the head, the middle, and the tail reaches, respectively, as compared to that produced before spate improvement [21].

4.2.2. Check and drop structures

Although spate diversion from canals with a series of earthen embankments/bunds is easy, the frequent reconstruction of the bunds is labor-demanding and maintenance is hard while water is in the canal. As a result, farmers always demand better control structures when schemes are being maintained or improved. The best alternative means for this case is by providing an intermediate design of combined check and drop structure [5]. This encompasses a drop structure, combined with an earthen embankment for heading up the flow to convey it onto a series of fields. This type of structure is observed in old traditional spate schemes with considerable drops between fields.

4.2.3. Flow-splitting structures

These structures are constructed on main or secondary canals where flood flows were traditionally shared proportionally among groups of farms or where it is necessary to reduce flood flows in canals to smaller/more manageable discharges [5]. It is good to design flow-splitting structures in close consultation with farmers and build them from local materials using gabions or dry stone pitching.

One approach used in Eritrea for splitting flow was to provide a tough flow division structure, built from gabions to split huge flows into two channels. This structure also provides a durable hard point that farmers can use to anchor temporary diversion bunds that can be adjusted from spate to spate to control the allocation of lower flows. An excellent picture of this gabion flow splitting structure is available in Ref. [5].

5. Improving sedimentation

Spate irrigation is as much about sediment management as it is about water management [5]. The sources of sedimentation in spate irrigation systems are mostly floods from mountainous catchments. The sediment transport load of these floods is commonly up to 5% and in some wadis can exceed 10% by weight. This is at least twice that occur in many perennial irrigation systems. Coarser sediments reduce the flow rate of the flood by clogging intakes and canals. The levels of command areas also gradually increase overtime by field sedimentation.

The command area level rise during the design life of the project has to be considered when improved spate diversion weirs and intakes are designed and constructed [22]. Because the upstream command areas are closer to the wadi and hence irrigated more frequently, they are usually affected by high sedimentation rates. On the other hand, sedimentation rate is lower in downstream command areas as they seldom receive water [5]. For example, sedimentation rates were from 8.3 to 31.6 mm/year in the upstream and from 5.2 to 8.6 mm/year in the downstream fields of the Sheeb spate irrigation scheme (Eritrea) [22]. **Table 2** shows the average sedimentation rates of different spate-irrigated fields.

The command area rise from an upstream field is estimated from the following Eq. [5]:

$$\Delta h = n^* d^* c/(1.4^* 10^6). \tag{1}$$

where: Δh = annual rise of upstream fields (m); n = number of yearly spate irrigation; d = irrigation depth per irrigation (m); and c = concentration of sediment by weight (ppm).

New intakes and canals have to be designed to cope with changes in wadi bed and/or field levels rising up to 50 mm/year [5]. In spate irrigation systems, the settling basins are not best options, and designing canals with non-uniform slopes and sections can improve the performance of Fokisa modern spate irrigation system in Tigray (Ethiopia) [23].

The following measures has to be considered when new diversions are proposed [5]: (i) in order to maintain the irrigable command area, estimates of the rise in command levels expected over the design life of structures (>25 years) should be developed and used to design weirs, intakes, and water control structures. (ii) Intakes associated with permanent raised weir structures should be provided with effective sediment sluices that are designed to be operated during the very short periods when flood flows exceed the diverted flows. (iii) Where intakes are not associated with permanently raised weirs, the provision of bed bars and breachable bunds, built from local materials, on top of the bed bars provides an improved intake that works in a similar manner to sediment management in traditional systems.

The scheme	Annual rise rate (cm/year)
Wadi Laba, Eritrea (Measured 2003/2004)	Upstream fields 1.0–3.5
	Middle fields 0.8–2.0
	Downstream fields 0.5–1.2
Wadi Laba Eritrea (Long-term estimate)	3.0
Eastern Sudan	1–3.9
Baluchistan mountain systems	>5.0
Wadi Zabid	Upstream fields 2–5

Source: Haile [1].

Table 2. Typical rates of sediment deposition.

6. Field water management and soil moisture conservation

The impact in crop production due to improving soil moisture conservation and managing field water allocation is at least equal with that of improving water supply [2]. Therefore, field water management and moisture conservation have to be integral components of spate irrigation improvement endeavors [6]. Their efficiency is affected by many factors: the nature and kind of field water-sharing arrangements; soil water-holding and infiltration capacities; the mode and timing of tillage and mulching practices; irrigation turns and gifts; water distribution rights and rules; and design, operation, and maintenance of field bunds.

6.1. Field water distribution methods

Field water sharing is regulated by water rights and rules in operation at the time and follows the following principles: flood water must be spread rapidly to avoid flood vanishing in low-lying areas; shared flows must be manageable to avoid erosion and gully formation; and large and sufficient water must be guaranteed for downstream areas in short period of spate flow availability [5]. The two common spate water distribution practices are:

i. Practices in command area water distribution: field-to-field distribution or individual field distribution; and

ii. Sizing of the command area: extensive distribution or intensive distribution.

6.1.1. Field-to-field water distribution/ individual field off takes

In most cases, there are no tertiary and secondary canals in field-to-field spate distribution systems. Hence, the entire flood flow in a canal is diverted to a group of fields divided by an earthen bund that blocks the canal. After irrigating the upstream field, water is released to the next field by cutting downstream field bund. This process continues until all the fields are irrigated [2].

The other option to field-to-field water distribution system is to provide fields from field inlets on secondary canals (controlled systems) [5]. This individual field intake is the norm in Pakistan whereas field-to-field systems are common in Yemen and in the Eastern Eritrea. There is a possibility of having these two systems in one scheme. **Table 3** shows the comparison of field-to-field and controlled systems.

It is recommended to implement a field-to-field water distribution system with a compact (smaller) command area under the single intake and single canal [6]. This type of distribution system rapidly lets huge amounts of flood water to fields within a short period of time spate is available. In Yemen and Eritrea, about 100–200 ha (divided into five blocks of 20–40 ha) are irrigated by one intake. Overflow structures such as simple stone pitched and concrete orifices (with stilling basins) have to be used to minimize field bund damage during excessive water application. Pictures of intakes and stone reinforced overflow structures in Pakistan, and stone-pitch overflow control structure in Tihama are available in Ref. [6].

Field-to-field irrigation	Individual field intake/controlled systems
• No land required for secondary canals, but possible damage to growing crops during second or third irrigation	• Land is required for secondary and tertiary canals though at the end of season canal beds are sometimes cultivated
• Smaller floods later in season are not diverted because upstream plots are cultivated	• Large gated flow control and division structures and field off-takes with a high flow capacity are needed—expensive
• In-field scour on the lands results from the breaching of downstream bund	• Gated control structures make it possible to divert water at any time in contravention to agreed water rights. This is not usually possible on a field-to-field system where diversion to fields is achieved using bunds constructed across canals.
• Smaller floods do not reach tail-end plots	• When plots are large, lack of leveling will create uneven irrigation
• The timing of breaching can be a source of conflict.	• Group water supply is not vulnerable to breaking of individual field bunds
• Damage of upstream field bunds may jeopardize flows to lower areas though compulsory maintenance is often regulated by local rules/laws	• Sedimentation in canals affects their ability to provide water to the tails

Source: Lawrence [2].

Table 3. Advantages and disadvantages of distribution methods.

6.1.2. Extensive or intensive water distribution

This method differentiates whether irrigation is distributed widely or concentrated in a narrow area at field level. Single irrigation is universal in extensive systems but two or three irrigations before cultivation are possible in compact/small area. The crop yield from two or three irrigations in a small area is more than two or three times that of single irrigation from a large area [1, 24]. This evidence was obtained from spate irrigation of sorghum crop in Yemen and sorghum and maize crops in Eritrea.

Therefore, compact area favors second irrigation, and promotes cooperation and investment for bund maintenance and land preparation before irrigation, because of a higher predictability of the spate irrigation system [5, 6].

6.2. Field water application and the importance of field bunds

According to Ref. [5], the height of field bunds is low where spate water supply is frequent and plentiful, normally in the upper fields and they are relatively higher in areas where spate water supply is erratic. In high field bunds of 2–3 m, water can inundate a land for long period and hinder timely tillage and land preparation, and are also not easy to maintain. Moreover, high field bund incurs high construction, maintenance, and operation cost to the poor, and consumes their time. Since the spate system is uncertain, its failure to provide the investment return may discourage farmers' future commitment. Therefore, according to Ref. [6], maximum field bund height limit was set to be 1 m.

Some of the techniques of improving field spate control and distribution are properly leveling field bunds to ease overflows over a long stretch, excavating a shallow trench downstream of the bund to distribute overflowing water over the total width of the field, the strengthening of spillway arrangements, and enhanced field gates [5].

6.3. Soil moisture conservation and improved agronomic practices

As crop yields can be hardly lowered by soil moisture deficit, moisture conservation is as important as water supply in spate irrigation. Techniques of soil moisture conservation in spate irrigation systems include soil mulching; mulching and intercropping; pre- and post-irrigation tillage; breaking soil crusts; practices of combined sowing and plowing; and encouraging the burrowing action of insects and crustaceans [5, 6, 25]. Crop yield can be increased by a factor of 1.5–3 through improved soil moisture conservation. For example, in Eritrean, sorghum yield was increased by 2 t/ha by practicing improved soil moisture conservation techniques such as mulching, pre-irrigation, and combined tillage and sowing [6].

Several cropping strategies have been developed by farmers to survive with the risks in spate irrigation. They grow high drought-tolerant local varieties in spate irrigated areas. Some of the major subsistence crops grown include sorghum, millet, pulses, and maize. After sufficient subsistence crops have been harvested, farmers usually grow cash crops like sesame or cotton [5].

According to Ref. [25], pre-irrigation plowing showed to be most effective in improving sorghum yield as compared to post irrigation plowing (**Table 4**). About 4 t/ha of sorghum yield was obtained in Eritrea where the combined sowing and tillage practice were used [26]. But, sorghum yield varies from 1 to 1.5 t/ ha in spate irrigated areas of Yemen and Pakistan where the combined practices are not implemented [26].

According to Ref. [27], the pre-sowing spate irrigation depths for the optimum wheat yield of 3448 kg/ha under spate irrigation would be 30–45 cm (September–July) in Pakistan. Pre-sowing depths of less than 30 cm and greater than 45 cm have resulted into the lowest wheat yields of 3302 and 3098 kg/ha, respectively. Farmers of Eritrea estimate that a person who has his own bullocks would be able to harvest a yield of 30–100% higher than another who does not own bullocks [5]. Because, with one's own draught animals, one could plow fields and

Land preparation	High floods (2.4 m^3/s)	Medium floods (1.6 m^3/s)	Low floods (1 m^3/s)
Pre-irrigation	4.29	2.14	0.86
Post-irrigation	2.25	1.07	0.43

Source: Avelino [25].

Table 4. Sorghum yield (t/ha) for gash agricultural spate scheme, Sudan.

repair bunds after every irrigation, thus vastly increasing soil moisture retention. Therefore, investments in infrastructure may be complemented by programs to ensure a better stock of draught animals.

From the most comprehensive assessment of yield in the spate irrigated and non-irrigated farm, wheat yield increased from 4 to 13 t/ha; barley from 7 to 12 t/ha; teff from 3 to 6 t/ha; haricot bean from 6 to 15 t/ha; and maize from 3 to 10 t/ha [28]. This shows that under spate irrigation, yield increase is significant for all crops.

Spate irrigated agronomic research that have to be studied and disseminated to farmers are: drought-tolerant and high-yielding varieties; improvement of inter-cropping systems, seed banks establishment, improved crop storage to minimize post-harvest losses, improved soil moisture conservation and management practices; and the integration of home-grown and technical knowledge with the scientific one [5].

7. Water rights, distribution rules, and managing inequity

7.1. Water rights and water distribution rules

In spate irrigation systems, water rights are expressed as "reactive water rights" as they express granted asserts and tolerable practices in a changing and unpredictable situation rather than quantifiable rights to a natural resource, as in perennial irrigation systems [2]. Water rights and rules help to establish water allocation rules in new systems, discover prospects for improvement in enforcement and revision of water rights, and consider new circumstances and how they affect distribution rules and avoid unplanned shortcomings of the anticipated changes [5].

Conflicts are spring to arise in the absence of agreement on water rights as spate irrigation being new in many areas. The results are sometimes dramatic. For example, the conflict on the Weida River in Konso (Ethiopia), where more than 200 persons were killed over a water dispute between investors and pastoralists, is an evidence for this [5].

As concluded by [29], tribal area systems working without state involvement in Punjab (Pakistan) have developed successful local irrigation managing institutions based on social and ecological significances to guarantee sustainable self-leading resource administrations. In contrast to this, the state interference in indigenous irrigation systems undermined collective action and distorted equity in access to traditional irrigation rights in state-managed areas in Punjab.

Rights and rules are also important to adapt to changes in the wadi morphology/courses and flood canals [2]. Codifying water rights and rules in documents can serve as a basis for clarifying disagreements [30]. The enforcement of rights and rules can decline, but the rights and rules become worthless without enforcement by local leaders, organizations, or government institutes [28].

The repertoire of water distribution rules was described by [2, 30]. In the Wadi Laba (Eritrea), the rule states that regardless of its location, the type of crop grown in it, and the social and economic status of its owner, a field is allowed a second turn only after all the other fields that are entitled to irrigation (in line with the rule on demarcation) have received one turn [29]. This rule has, however, some practical shortcomings. In Wadi Tuban, Yemen and Rod Kanwah, Pakistan, the rules limit the access to second turns only to the most important subsistence crops such as wheat in Pakistan and red sorghum in Yemen [30].

7.2. Managing inequity and uncertainty

In spate irrigation, a certain degree of inequity between upstream and downstream users—between and within systems—is inevitable. Ensuring the command area that is not too enlarged can alleviate this. A smaller command area will make it more likely for farmers to have two or more floods, which can highly increase productivity as crops are no longer in the "stress zone" [15].

According to [31], for example, in Bada (Eritrea), a number of mechanisms to reduce inequity in water distribution are: first is the prevalence of the permanent channel network that avoids water that is concentrated excessively in the upper reaches, as is the case in a field-to-field irrigation. The second set of rules that modify the difference between upstream and downstream fields are the restrictions on second turns and the practice of distributing water to the driest fields first in times of water scarcity.

8. Summary and recommendations

8.1. Summary

In this chapter, the needs for and ways of improving traditional spate irrigation systems were reviewed in detail. Spate irrigation is the science and art of diverting floodwater from dry river beds or seasonal rivers and using it for crop or pastures production, water supply for human and livestock, groundwater recharge, and tree plantation. To maximize the productivity of drylands with high spate irrigation potential, traditional systems of spate irrigation has to be improved. In this case, farmers should be consulted and involved using their indigenous knowledge in the planning, design, and implementation of improvement works. The modernization interventions which fail to consider these, in many cases, were not successful. On the other hand, the best successful improvements incorporate less labor intensive and relatively permanent structures with the advantages of conventional systems (technical and social aspects) without considerably altering the approach of the spate irrigation practice.

Hence, the improved spate irrigation systems must be designed so as to minimize the damage of canals and fields by large floods. These systems must guide and split flood flows, rather than constrain them, avoid excessive sediment load in spate irrigation systems and ensure that suspended sediments should not be deposited in the canals. Their design must also ensure that they can cope with recurrent and occasionally big changes in river beds.

In addition, spate irrigation improvement packages should adopt a field-to-field water distribution system with compact (smaller) command area under one intake and one canal instead of an individual field water distribution system; limit maximum number of irrigation turns to two; limit field bund heights to 1 m; 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; and grow drought tolerant local variety crops.

In spate irrigation systems, it is not advisable to have gated intakes as they are difficult to operate with high floods coming at odd hours; hence, open gates are recommended. In spate irrigation systems, the objective is to divert the maximum possible amount of water to irrigate as many fields as possible during the very limited period of the spate flood availability. Hence, the intakes and canals must have a much larger discharge capacity per unit area served than would be the case in perennial irrigation schemes. The deflection angle of the intakes should be minimized to reduce sediment entrance. The design of the canal command levels needs to take account of the likely rise in field levels (due to sedimentation) during the design life of the proposed improvements to the canal intake.

Water rights in spate irrigation should be "reactive water rights" since they describe agreed claims and acceptable practices in a changing and variable environment. A certain degree of inequity between the upstream and downstream user and conflicts can be minimized when water rights and rules are enforced. Farmer-managed spate irrigation systems are more sustainable than those with much government interference.

In conclusion, the review investigates that the science and art of spate irrigation is the least understood, the least researched, and the least documented. Therefore, this review chapter helps as a reference material for teaching, training, and research activities and would play a great role in the sustainable spate irrigation system development, rehabilitation, and management work.

8.2. Recommendations

The following gaps were identified from the review. Spate irrigation is yet different from conventional irrigation in many ways. In spate system, farmers are interested in diverting a large amount of flood. In this case, a large amount of sediment could get into canals and irrigated fields and spate structures could also be damaged. Therefore, optimal design of spate irrigation systems which both maximize the amount of water diverted and minimize structural damage and sedimentation problems is required. Spate irrigation is also the least researched and the least understood among irrigation engineers, managers, and the users, and the least documented. Moreover, spate irrigation is not yet a part of the curriculum of many academic institutions. Hence, in order to exploit the available spate irrigation potential for food security and livelihood improvement, the following are suggested for the improvement of traditional spate irrigation systems:

- Capacity building and experience sharing programs on successful and improved traditional spate irrigation system, are required for professionals, practitioners and farmers, agro-pastoralists, and others who involve in spate irrigation development. In this case, technical or engineering aspects (design of intakes, canals and command areas), soil and water management, agronomy, water rights and distribution rules, environmental and institutional aspects of spate irrigation should be attended to the trainees.
- Incorporating separate spate irrigation courses at higher educations.
- Farmer-based on-site research such as (i) the impact or combined impacts of field bunds, pre-irrigation and post-irrigation tillage on soil moisture storage, and crop yield, and (ii) different short duration, drought and flood tolerant, and high yielding crop, orchard or tree varieties.
- Research on optimal design of improved traditional diversion structures, canals, and canal structures that maximize the amount of flood water diversion and that minimize the structural failure and sedimentation problems. For example, the effect of improved traditional intake size on sedimentation of traditional improved canals, fields, the size of the irrigated area, and cost-benefit analysis associated with improvements, etc., are not well studied.
- Research on social aspects of spate irrigation is as important as technical aspects (for example, water and land distributions, spate use and rights, the participation of irrigators in the spate irrigation development and management).

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