Flexibility as a strategy to cope with uncertain water supply in spate irrigation*

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Abstract
Unpredictable flash floods in ephemeral rivers are the water source for spate irrigation systems. An important element in the success and sustainability of spate irrigation systems is their ability to cope with highly uncertain water supply and high sediment load. Flexibility is considered one of the key ingredients of coping strategies. However, the concept of flexibility in the context of spate irrigation systems is poorly defined. A framework to assess and operationalize flexibility in spate irrigation is lacking. In this paper we develop a conceptual framework by answering four principal questions and exploring eight flexibility characteristic features and five subfeatures. We explore the flexibility of traditional, improved and modernized spate irrigation systems to cope with high, low and untimely flood events. Flexible spate irrigation systems are highly dependent on system capabilities to deal with uncertainty and enable adjustments to change. The framework can be used as a guideline for water managers, farmers and decision makers for assessing and providing flexibility in spate irrigation systems.

KEYWORDS
flexibility framework, Gash agricultural scheme, real options, unpredictable floods, water supply variability

Résumé
Les crues soudaines imprévisibles dans les rivières éphémères sont la source d’eau des systèmes d’irrigation de crue. Un élément important pour le succès et la durabilité des systèmes d’irrigation de crue est leur capacité à faire face à un approvisionnement en eau très incertain et à une charge sédimentaire élevée. La flexibilité est considérée comme l’un des ingrédients clés des stratégies d’adaptation. Cependant, le concept de flexibilité dans le contexte des systèmes d’irrigation de crue est mal défini. Un cadre pour évaluer et opérationnaliser la flexibilité dans l’irrigation de crue fait défaut. Dans cet article, nous développons un cadre conceptuel en répondant à quatre questions principales et en explorant huit caractéristiques de flexibilité et cinq sous-caractéristiques. Nous explorons la flexibilité des systèmes d’irrigation de crue traditionnels,

* La flexibilité en tant que stratégie pour faire face à un approvisionnement en eau incertain dans l’irrigation de crue.
Spate irrigation is a type of flood-based farming that makes use of highly variable and seasonal flash floods in ephemeral rivers, often one of the few available water sources in arid and semi-arid regions. Spate irrigation systems need to cope with a high level of uncertainty and unpredictability regarding flood size and timing. Additionally, spate irrigation systems are exposed to continuously changing socio-economic and physical conditions. Changes in physical conditions include alteration in river (or wadi) morphology due to erosion and sediment deposition, increase in command area level and destruction of irrigation infrastructure. The socio-economic dynamics include changes in policies that affect agricultural production, access and distribution of water, access to technology and seasonal migration. Therefore, farmers and their institutes have to deal with climate change and climate variability through short-term and/or long-term measures to uncertain water supply and policies. In traditional and improved systems, farmers use coping strategies to respond to unexpected variability, while in modernized systems, adaptation strategies are used to adjust to long-term changes.

A big challenge in the planning of spate irrigation systems is the design of engineering works. Because of the lack of historical records of river flow and sediment transport data, most spate irrigation systems are designed based on empirical methods and assumptions. Even if historical records are available, the design of hydraulic structures using deterministic and probabilistic forecasts assumes hydrological stationarity (Major and Frederick, 1997; Schulz et al., 2000) which may not be valid in areas with very high climate variability and change (Frederick et al., 1997; Lempert, 2003). Seasonal flash floods, the main water source in spate irrigation, are characterized by sequences of short-duration high flood peaks, high flow velocity and large sediment load that could lead to damage to life, property and infrastructure (Borga et al., 2011; Creutin et al., 2013). At other times, these floods may reduce to small flows which are unusable for irrigation. With these high levels of changeability and unpredictability in water supply, it is challenging to plan, operate and take action. Farmers and water managers are uncertain about pre-season decisions on irrigation plans, irrigable area, irrigation duration, decision on operation of intakes and offtakes, level of maintenance, and level of investment in farming activities and land preparation.

To cope with uncertainties in water resources and flood water management, several studies have recommended maximizing flexibility in design and operation (Working Group II of the Intergovernmental Panel on Climate Change (IPCC), 2007; Huang et al., 2010; Turral et al., 2011). For example, the FAO publication ‘Guidelines for spate irrigation’ recommended a flexible approach to spate irrigation improvement to cope with changing conditions, frequency and severity of extreme events and uncertainty (van Steenbergen et al., 2010). Flexibility of spate irrigation systems (traditional, improved, modernized) depends on the availability of viable actions and decisions at the river diversion, the canal network and irrigated fields. So-called traditional spate systems were generally regarded as the most flexible, having flexible water rights (van Steenbergen et al., 2010; Kamran and Shivakoti, 2013), flexible irrigation turns (Mehari Haile et al., 2005c, 2011) and flexible control of intakes (van Steenbergen et al., 2010). For example, Mehari Haile et al. (2005c) described flexible water rights and rules between different farmers in Wadi Leba in Eritrea such as flexible land and water scheduling, proportional distribution of flood water, flood water distribution based on flood size; and rules on canal breaching to avoid downstream damage (Mehari Haile et al., 2003). van Steenbergen (1997) recommended the use of flexibility in the engineering design of spate irrigation systems to accommodate water supply variability. The so-called modernized systems are considered the most rigid, with claims that the lack of flexibility contributed to their failure (van
While flexibility is widely recommended as a strategy to cope with unpredictable water supply in spate irrigation systems, there is no in-depth analysis on the subject. The main objectives of this study are to develop a conceptual framework for the inclusion of flexibility in the context of spate irrigation and to assess the flexibility of traditional, improved traditional and modernized spate irrigation systems. Based on data collected from primary and secondary sources, this research assesses the flexibility of traditional, improved traditional and modernized spate irrigation systems, in addition to the different flexible options to cope with unpredictable, uncertain and highly variable water supply. It included more than 100 interviews with farmers, water users’ associations (WUAs) and water managers from the Gash spate irrigation system (GAS) in Sudan (Fadul et al., 2019); a literature review of existing technologies in different countries such as Yemen (Mehari Haile et al., 2011; Spate Irrigation Network (SIN), 2013b), Pakistan (Mehari Haile et al., 2011; Khan et al., 2014), Eritrea (Mehari Haile et al., 2011), Iran (Kowsar, 2011), Morocco (Oudra, 2011), Sudan (van Steenbergen et al., 2011a, 2011b, 2011c; Zenebe et al., 2015), Myanmar (SIN, 2013a) and Ethiopia (Liebsek et al., 2015; Castelli et al., 2018; Tadesse and Dinka, 2018), and information gathered during a regional workshop on farmer to farmer knowledge sharing conducted in 2012 in Sudan (Fadul et al., 2012). The interviews, regional workshops and available literature helped to identify real options during high, low and untimely floods, and to explore flexibility elements in different spate irrigation systems and their capabilities.

2 | EXISTING SPATE IRRIGATION SYSTEMS AND PRACTICES

Different technologies are being used in spate irrigation for river diversion, irrigation conveyance networks and field application. Usually they are categorized as traditional, improved traditional and modernized systems (Table 1) (van Steenbergen, 1997; Mehari Haile et al., 2005a; van Steenbergen et al., 2010; Komakech et al., 2011; Kowsar, 2011; Mehari Haile et al., 2011; van Steenbergen et al., 2011a, 2011b, 2011c).

2.1 | Traditional spate systems

The practice of spate irrigation has a long history. Traditional systems are built and maintained using farmers’ indigenous knowledge and skills, local materials

| Location | Traditional system | Improved traditional system | Modernized system |
|----------|--------------------|-----------------------------|------------------|
| Diversion | Soil bunds/spurs (Figure 1), open intakes (Yemen, Eritrea, Pakistan, Ethiopia), earthen deflecting spurs (Iran, Sudan, Morocco, Myanmar, Yemen), brushwood dam with wooden piles (Iran, Myanmar), diversion weir, terraces with weep holes drainage (Iran) | Reinforced soil bund-spur, gabion diversion and stabilizers (Iran, Pakistan, Ethiopia), drop-off structure, bed stabilizers (Pakistan), brick mortar, masonry intakes (Figure 2) (Sudan, Iran, Ethiopia), masonry check dams (Iran), wooden stop-log intakes, stone gabion open intakes (Yemen), rejection spillway fuse plugs (Eritrea, Pakistan, Yemen, Ethiopia) | Concrete weir and gated concrete intake (Figure 3), automatic intakes (Iran), settling stilling basin (Yemen, Morocco, Myanmar), sluice gate (Myanmar) sediment excluders (Morocco, Yemen, Pakistan, Myanmar), rejection spillway (Yemen, Morocco) sluice gate (Myanmar) |
| Distribution | Several short canals, flow splitters (Pakistan, Yemen), stone wall (Yemen) | Earthen main canal, tertiary canal, guide wall (Morocco) | Long single main canal, controlled cross structures, secondary canal (often), tertiary canal, conveyance spreader channel (Iran) |
| Field | Field to field (Yemen, Eritrea) | Individual field inlets (Sudan, Pakistan), gated offtakes, masonry drop-off structure (Iran), gated orifice | Individual field inlets (Pakistan), gated field offtake, field canal, field spurs, field embankment, open/closed-end field, tail drain (Iran) |

Note: Table 1 is compiled from various sources: (Camacho, 1987; Mehari Haile et al., 2005a; van Steenbergen et al., 2010; Kowsar, 2011; Oudra, 2011; SIN, 2013a, b; Liebsek et al., 2015; Castelli et al., 2018; Tadesse and Dinka, 2018).
and resources without external support (van Steenbergen et al., 2010; Mehari Haile et al., 2011). Traditional intakes and diversion weirs are designed to minimize interference with the flow path of floods in river channels. The weirs made of sticks and stones are washed away during medium to large floods and hence prevent large and potentially destructive, high-sediment-laden floods from entering the canal system (van Steenbergen et al., 2010). The diversion system consists of a series of small diversion weirs which allow downstream users to divert flood water even when large floods breached upstream weirs. Traditional intakes need frequent maintenance and reconstruction after each large flood, which requires strong collaboration between all farmers (Camacho, 1987; van Steenbergen et al., 2010). Additionally, the practice of field to field irrigation, whereby flood water has to pass through the same top field to irrigate the next fields, results in over-irrigation and sediment build-up in head fields (van Steenbergen et al., 2010).

2.2 | Improved traditional systems

To overcome these drawbacks, in some traditional systems improvements have been made to ensure less labour-intensive and relatively permanent structures, without major alterations to existing practices (Mehari Haile et al., 2005a, 2005b; van Steenbergen et al., 2010; Castelli and Bresci, 2017; Castelli et al., 2018; Tadesse and Dinka, 2018). These improvements include the use of adjustable stone or masonry weirs with breach or overflow sections; improved diversion bunds with bed stabilizers to replace earthen and stone structures; reinforced intakes with bricks and mortar; and structures to better control water distribution along the main canal. At field level an improved field to field system is introduced through the use of drop structures made of masonry to reduce scour risk.

2.3 | Modernized systems

Modernized systems are characterized by the use of permanent structures made of concrete, a sediment exclusion system and an irrigation network consisting of one single main canal and secondary, tertiary and field canals which allow the supply of water to individual fields.
Modernized systems are sufficiently robust to tolerate variability and divert both advance and recession flow including (reasonably) high floods which cannot be diverted by traditional systems. Nevertheless, if existing rules and practices are not acknowledged during design and operation, a modernized system will lead to unfair water distribution by favouring the upstream farmers with more water access (Mehari Haile et al., 2011). Failure of modernized systems in countries such as Ethiopia, Yemen and Pakistan occurred partly due to the diversion of large floods with high sediment load, poor design and the low involvement of farmers in the development, design and construction processes (van Steenbergen, 1997; Oosterbaan, 2010; van Steenbergen et al., 2010; Komakech et al., 2011; Mehari Haile et al., 2011; Libsekal et al., 2015; Castelli and Bresci, 2017). Traditional systems are limited to shallow depth rivers and wadis (Mu’Allem, 1987; Zaqhloel, 1987), while modernized systems can tap from deeper rivers (Mehari Haile et al., 2005a).

A systematic framework to better understand flexibility and to provide a conceptual approach to formulate flexible real options in the planning, design and operation of spate irrigation systems is still lacking. Therefore, next section novelty describes the structure of a conceptual framework for inclusion of flexibility in the context of spate irrigation.

3 CONCEPTUAL FRAMEWORK FOR FLEXIBILITY IN SPATE IRRIGATION SYSTEMS

There is a large body of literature on the concept of flexibility, outlining general principles and operationalizing in a number of different fields such as software system architecture (Schulz et al., 2000), aerospace systems (Saleh et al., 2003), urban and infrastructure development (De Neufville and Scholtes, 2011), emergency management (Ward et al., 2015), information technology (Dorsch, 2015), water supply and waste water systems (Spiller et al., 2015) and flood defences (Anvarifara et al., 2016).

The proposed framework to conceptualize flexibility in spate irrigation systems is adapted from established paradigms for water resources management, coastal flood defence (Anvarifara et al., 2016) and integrated coastal management (Taljaard et al., 2011). Anvarifara et al. (2016) identified eight features of flexibility, namely: change, uncertainty, goals, capabilities, mode of response, temporal dimensions, and real options and enablers. Similarly, Difrancesco and Tullos (2014) identified five flexibility characteristics which are relevant to water resources systems, namely: slack, redundancy, connectivity, coordination and adjustability. Both fields of flood defence and water resources management are relevant to spate irrigation systems in terms of exposure to uncertainty of climate parameters and possible changes of the system. The two frameworks complement each other: the flood defence framework conceptualizes the understanding of flexibility in flood management, while the water resources management framework highlights actions and decisions to adjust to changing conditions. Therefore, we propose a combination of the two conceptual frameworks with a few modifications to assess flexibility and formulate real options in spate irrigation systems. Following Anvarifara et al. (2016), the framework with four self-guiding questions has been developed. The combined framework is presented in Figure 4.

1. Why is flexibility needed? (Q1)
2. What is it that flexibility is required for? (Q2)
3. What are the dimensions of flexibility? (Q3)
4. What needs to be changed or adapted? (Q4)

In Table 2 a general description and characteristic features of the terms used in the conceptual framework are thoroughly listed as follows.
3.1 Description and application of the framework in the context of spate irrigation

3.1.1 Why is flexibility needed?

Change. External sources relate to changes in the system resulting from climatic factors and consequent effects, such as a sudden rise in the peak flood, an extended duration of high flood levels, an unpredicted low flood season, the occurrence of an early or late flood. Types of flood risks in spate irrigation are described in detail by van Steenbergen et al. (2010) and Fadul et al. (2018). Major internal changes include a sudden breach in the river or canal embankment, escaped intakes, blockage of canals with sediment, failure of diversion weirs and changes in duration of the irrigation season (Mehari Haile, 2007).

Uncertainty results from the unpredictability of flood size, rate, duration and timing. Other sources of uncertainty are related to lack of knowledge and information on technology, maintenance, and suitable design approaches that consider the pattern of rising hydrographs (van Steenbergen, 1997; van Steenbergen et al., 2010). Uncertainty might lead to ad hoc operational decisions such as when to open or close an intake while not knowing when the next flood opportunity will come.

3.1.2 What is flexibility required for?

Goals represent the desired objectives of flexibility which could handle both upsides and downsides of uncertainty and changes (Anvarifara et al., 2016). Goals differ by system type and location based on benefits, risks and costs; additionally they can be changed towards adaptation. For example, in a modernized system in Pakistan, the goals are to increase productivity, improve national food security and livelihoods while minimizing failure of irrigation. In the improved system of GAS in eastern Sudan, the goals are to increase irrigated area and minimize failure of structures. In traditional systems the goals are often to minimize the risk of diverting high floods. In general, maximizing the opportunities and minimizing the risk in spate irrigation are affected by the type of technology and the level of investment (Table 3). Further, the improvement of traditional systems towards developing adaptation strategies requires change in goals in the long term such as exploring a diverse range of water supply sources in addition to existing traditional sources (Wong and Brown, 2009).

3.1.3 What are the dimensions of flexibility?

Capabilities are the system’s characteristics that enhance its flexibility to make necessary adjustments to cope with change and uncertainty. Capabilities are described by the subfeatures (Difrancesco and Tullos, 2014): redundancy, achievability, coordination, connectivity and slack. The characteristics that determine system capabilities differ by system type (as summarized in Table 4). Redundancy refers to the total number of options that can be achieved to meet future needs (Slack, 1983; Gerwin, 1993; Volberda, 1996). In the spate irrigation context, redundancy is provided by the number of intakes, bypass canals, flood depression zones and surface storage options; the number of organizations, or agencies, for delegation of responsibilities such as maintenance and financing; and the number of alternative

| Questions                                      | Characteristic features | General description                             |
|------------------------------------------------|-------------------------|-------------------------------------------------|
| 1. Why is flexibility needed?                 | (a) Change              | Internal and external                           |
|                                               | (b) Uncertainty         | Unpredictable, unplanned or uncertain           |
| 2. What is flexibility required for?          | (c) Goal                | Minimizing water supply risks and maximizing irrigated area |
| 3. What are the dimensions of flexibility?    | (d) Systems capability  | Range/number of options and quickness of implementation |
|                                               | (e) Temporal            | Short, mid and long term                        |
|                                               | (f) Mode of response    | Proactive–reactive                              |
| 4. What needs to change or be adapted (with farmer involvement)? | (g) Real options (adjustability) | Decisions: expand, defer, shrink, update, add, modify |
|                                               | (h) Enablers            | Sources of alterations in the technical design and management decision |
decisions on water-sharing period and irrigation plans. For example, in Iran a number of reservoirs and individual terraces were built to accommodate different flood sizes (Kowsar, 2011). In Myanmar a pump system along river banks was implemented to pump excess water to supplement spate irrigation canals when needed (SIN, 2013a). In Pakistan and Yemen, improved traditional systems can use a number of options to cope with high peak floods such as bed stabilizers, flow dividers and reinforcement of earthen structures (van Steenbergen et al., 2010).

Achievability refers to the ability to implement a measure rapidly in a cost-effective manner. The use of simple and less complex technologies is considered one of the advantages of traditional spate irrigation systems, supporting timely decisions and rapid actions such as

| TABLE 3 | The need and goals of flexibility for different types of spate irrigation systems |
| --- | --- | --- | --- |
| Flexibility question | Flexibility characteristic features | Traditional system | Improved traditional system | Modernized system |
| 1. Why is flexibility needed? | (a) Change | Water level increase in the river at intake | Water level increase in the river at intake | Large diversion of sediment at the intake |
| | (b) Uncertainty | The extent of the increase in water level | The extent of the increase in water level | The extent of sediment intrusion |
| 2. What is flexibility required for? | (c) Goal | To prevent high flood diversion and minimize damage | To manage flood peak diversion and maintain irrigation | To accommodate peak flood and maximize irrigation |
| | | Avoiding costly interventions | Reducing cost of current intervention | Reducing the cost of future intervention |

| TABLE 4 | System capabilities for different spate irrigation systems |
| --- | --- | --- | --- |
| (d) Capabilities | Traditional system | Improved traditional system | Modernized system |
| 1. Redundancy | High: a number of intakes, a number of fields (field and field system) | Very high: a number of intakes, a number of field to field systems, a number of individual field systems | Poor: one intake |
| 2-Achievability | Simplicity | High: easily rebuilt, maintained, relocated; use of local material and knowledge; farmer-managed systems | Medium: easily built; farmer with support of local government management system | Low: complex system; local government in partnership with farmers’ agency management system |
| | Cost | High maintenance cost including labour input | Average | Low maintenance cost, high initial cost |
| | Information system | Less dependent | Moderately dependent | Moderately to highly dependent |
| | Human power | Largely dependent on the number of farmers | Dependent on experienced farmers and engineers | Less dependent on farmers, highly dependent on qualified engineers and labour |
| 3. Coordination | Cooperation between u/s and d/s farmers | Farmers–water managers–governmental agencies, upper catchment | Water managers–governmental agencies, upper catchment |
| 4. Connectivity | Highly connected to ecosystem and groundwater recharge | Highly connected to ecosystem and groundwater recharge | Highly connected to ecosystem and groundwater recharge |
| 5. Slack | Low: built to withstand only average and low floods | Average: spillways, scope to increase embankment and structure height | High: storage options and excess capacity |
relocating intakes and structures or rebuilding with local materials (Mehari Haile et al., 2006; van Steenbergen et al., 2010). In the GAS (Sudan) water managers can make quick decisions about the start of the irrigation period based on observations of the river (Fadul et al., 2019). In acute water-scarce situations they can decide to allocate water to those farmers who have paid their water fees or have done field preparations, excluding those who are not ready (Fadul et al., 2019). Other forms of achievability include established mechanisms to access climatic and hydrological flow measurements and irrigation data; and institutional arrangements to maintain skilled labour for operation and maintenance of complex systems.

Coordination refers to intra-basin and system coordination between water managers and agencies related to the operation and management of water resources and flood management with due attention to regional coordination. For example, in Sudan during the flood season, coordination between the River Training Unit in the Ministry of Water Resources and the irrigation authorities in the improved traditional system of the GAS contributes to timely and appropriate operational decisions during high peaks and untimely floods and facilitates maintenance activities by borrowing heavy equipment (Fadul et al., 2019). In traditional systems, cooperation between upstream and downstream farmers is essential for joint construction and rebuilding of weir and diversion bunds (Mehari Haile et al., 2011). Modernized systems rarely make use of farmers’ cooperation for operation and maintenance which may have contributed to the failure of some modernized systems in the Raya valley in Ethiopia (Castelli et al., 2018).

Connectivity refers to the ability of system components to attach to other components inside and outside the system (Difrancesco and Tullos, 2014); in other words, it refers to the physical attachment of system components. In spate irrigation, conjunctive use of groundwater and surface water, infiltration basins and watering ponds are some forms of connectivity. Conjunctive use of canal water and groundwater enhances the flexibility of irrigation services (SIN, 2013a; van Steenbergen et al., 2010). In Hadramut (Yemen) the use of a subsurface dam and low-level weir for groundwater recharge was one of the objectives of spate water management (van Steenbergen et al., 2011a, 2011b, 2011c).

Slack refers to the ability of a system to provide surplus capacity and excess sizing to cope with changes and uncertainty. Having excess capacity to divert, convey and store excess flood water creates opportunities to benefit from an increased irrigated area, increased urban water supply and groundwater recharge. Difrancesco and Tullos (2014) argue that provision of slack in the form of bypasses and spillways provides a more cost-effective means to prevent flood damage than reinforcement and heightening interventions. Slack in a spate irrigation system could be described by the degree of excess capacity that gives room for future adjustments to cope with changing conditions. A common provision of slack for coping with rising water levels is the option to delay interventions until uncertainties unfold over time (Anvarifara et al., 2016; Fadul et al., 2019). An example of this is the choice of increasing the width of an embankment to allow for future heightening, or the provision of space around embankments for future decisions on widening and heightening (Woodward et al., 2011). In the traditional spate irrigation system in Baluchestan (Iran) slack is provided by increasing storage capacity through a stone wall dam constructed across a narrow valley and connected with a spillway. The wall is protected against excess high floods by the provision of drainage through weep holes (Kowsar, 2011). In a modernized spate system in Iran, slack is provided by the construction of tail-end drains, spreading excess flood water over an extended area and using groundwater recharge basins (Kowsar, 2011). To handle high peaks, excess flood water is sometimes diverted to forests and rangeland (van Steenbergen et al., 2010). For example, in Iran excess flood water diverted to orchards yielded 20 000 t of figs (Kowsar, 2011). During low flood events, slack is about finding additional water sources such as conjunctive use of groundwater, field water harvesting and sharecropping.

The quantitative assessment of a system’s capability requires metric descriptions of each subcomponent of flexibility (i.e. redundancy, achievability, coordination, connectivity and slack), an example of which can be found in Difrancesco and Tullos (2014). In this research we used a general description and assumptions to illustrate the application of the framework. Quantification is beyond the scope of this paper.

Mode of response describes the attitude of decision makers based on the effects of change (Golden and Powell, 1999), before (proactive), during and after (reactive) occurrence of events. During and after events actions are event-driven, aimed at reducing the negative consequences of impacts and losses (Evans, 1991), while actions and decisions before the event (proactive) anticipate external changes by taking measures to prevent negative impacts and pursue possible opportunities (Triantis, 2000). Fadul et al. (2019) discussed the measures and decisions taken before, during and after events in response to high flood risks by water managers, water users’ associations (WUAs) and farmers in a spate irrigation system in Sudan. The mode of response of water managers and WUAs were mostly before and during events (proactive); however farmers’ response was mostly after the events (reactive), reflecting the risk-averse behaviour in subsistence farming systems (Table 5).
Temporal dimension indicates the period of time during which the change needs to occur (De Toni and Tonchia, 1998). There are three categories for the temporal dimension of flexibility: short, medium and long term. Short-term flexibility concerns timely and quick reactions to short-term, discrete changes that occur during or after an event. Examples of such events in spate irrigation are: a sudden rise in flood peak, overtopping of diversion intakes, breaching of river and canal embankments. Long-term flexibility concerns the process of changes (relatively permanent) in actions and decisions such as change in irrigation requirements (Palmer and O’Keefe, 2007), land entitlements, constructing new canals or irrigation structures, change of irrigation source and abandonment decisions.

3.1.4 What needs to be changed or adapted?

Real options refer to a group of actions and managerial decisions for adjustability as a response to change and uncertainty (Myers, 1977). It includes options to adapt as well as options to cope (Difrancesco and Tullos, 2014). The concept of real options was first introduced by Myers (1977) which means the ‘right, but not an obligation’ to change/modify any system to adapt to a changing environment (De Neufville and Scholtes, 2011; Anvarifara et al., 2016). Real options are distinct from alternative choices by having the possibility to revise a decision at any time (De Neufville, 2002). Decision making in spate irrigation involves high uncertainty regarding flood volume, and duration before and during the irrigation season, which calls for an adaptive approach consisting of real options because future outcomes are not known. Real options allow for multiple decisions made over time as more information becomes available on events and impacts (Linquiti and Vonortas, 2012). Inflexible decisions (non-real options) use a deterministic approach for designing optimal strategies, based on a single fixed design value (such as diversion intake level, embankment height). Many designs of modernized spate irrigation use conventional design methods based on deterministic forecasts of the most likely scenarios or empirical methods, often followed by improvements in response to changes in river bed level and economic development. System capabilities should be able to support the actions and decisions to cope with a changing situation. The adjustability of actions is the ability to expand, defer or shrink (Trigeorgis, 2005). Adjustability of decisions is the option to delay or update. Adjustability to adapt refers to the ability to add, modify or remove any component of the system with ease. An important consideration in the flexibility framework is the engagement of farmers in the solution for the change. The decisions and actions with regards to adjustability must involve farmers’ participation in the development of any alteration, such as adding a new or improved structure and making managerial decisions to add, update, change goals or delay. Considering farmers’ preferences allows the integration of best traditional practices in the technical design of new or improved options (Castelli et al., 2018).

Enablers or flexibility mechanisms (Mikaelian et al., 2011) refer to the facilitators or the enabling environment necessary for adjustment to take place. Provision of an enabling environment for flexibility requires putting in place supporting measures to enhance efficiency of adaptation and coping strategies with proper attention to a participatory approach that explicitly includes farmers. This includes, but is not limited to, policy and institutional support, capacity building and empowerment mechanisms.

4 REAL OPTIONS AS COPING/ADAPTATION MECHANISMS

This section assesses real options used in different spate irrigation systems to cope/adapt to high, low and untimely floods.

| TABLE 5 Dimensions of flexibility for different types of spate irrigation systems* |
|-----------------|-----------------|-----------------|-----------------|
| Flexibility characteristic features | Traditional system | Improved traditional system | Modernized system |
| 3. What are the dimensions of flexibility? | (d) System Capabilities | High redundancy | Very high redundancy | Poor redundancy |
| | | High simplicity | Medium simplicity | Low simplicity |
| | | High maintenance cost | Average maintenance cost | Low maintenance cost |
| (e) Temporal | Change is temporary and short term | Change is gradual, discrete and short term | Change is permanent, and long term |
| (f) Mode of response | A reactive response, after event | A reactive response during and after event | A proactive response |

*Table 4 describes system capabilities in more details
4.1 | High flood event

In traditional spate systems, high peak floods lead to the collapse of upstream weirs and earthen bunds. Although traditional systems have several diversion intakes along the river to enhance the possibility of irrigating at least some of the area (van Steenbergen, 1997), farmers are still uncertain about the failure of the downstream intakes. They are also uncertain regarding the extent and recurrence of high floods. The flexibility of traditional systems stems from their simplicity, ease of adjustability in changing layout, moving location to a more stable section or even making a new diversion weir using locally available materials. Because of these flexibility features, real options to cope with high floods are related to timely decisions and actions of rebuilding or relocating intakes to catch some of the later floods. The flexibility to rebuild or relocate damaged intakes, using locally available materials, is to a large extent dependent on the participation of all farmers (enablers). For example in Myanmar, community participation resulted in increase of the irrigated area in dry zones (SIN, 2013a). However, the cost of rebuilding flexibility is high due to high labour and resource requirements.

Improved traditional systems are more robust in managing high floods than traditional systems, using gated and reinforced structures to protect the command area from damage during large and uncontrollable floods. However, sudden rises in high water level and peak flows can result in failure of embankments of the river and canals, and in high pressure on the system due to a lack of clear decision making in gate operation (Fadul et al., 2019). Changing the size of structures and embankments provides slack and the availability of several intakes provides redundancy to secure diversion to at least some part of the area. Being able to adjust operational decisions on the diversion of potentially destructive high floods enhances system flexibility and creates real options to cope with uncertainty. For example, in eastern Sudan, an improved traditional diversion system in the GAS can irrigate up to 100 000 ha of command area using gate control intakes, a spur system to stabilize channel beds, and riverbank stone pitching. The operational plan in the GAS is based on closure of intakes during the passage of very high flood peaks. Although weak river embankments are occasionally exposed to failure, this also provides opportunities for some unplanned area to be irrigated. In Morocco, triangular dissipation structures are constructed using successive gabion spillways to allow safe distribution of water (Oudra, 2011). In Iran, bank stabilization using brushwood and river bed stabilization using gabion aprons are common (Kowsar, 2011). Gabion structures in the Punjab (Pakistan) provide a flexible and cost-effective option for bed stabilization (Oosterbaan, 2010). In the Harosha spate system in Ethiopia, farmers block very high floods from entering the irrigation system by inserting earth piles at the intakes and building fuse plugs at the end of diversion structures (Castelli et al., 2018).

Being most robust, the modernized system can handle high peak floods, though this may encourage morphological changes due to erosion or build-up of sediment at upstream diversion bunds (van Steenbergen et al., 2010). The capacity of the field system is influenced by canal sedimentation and requires a high initial investment cost (van Steenbergen et al., 2010). Additionally, water managers are uncertain of the extent of sediment accumulation in the system. The high sediment load entering the intake and canals during high flood events is a big concern for modernized systems, leading to degradation of irrigation infrastructure, poor water distribution and system failure (van Steenbergen, 1997; Oosterbaan, 2010; van Steenbergen et al., 2010; Komakech et al., 2011; Mehari Haile et al., 2011; Libsekal et al., 2015; Castelli and Bresci, 2017). Modernized systems tend to make adaptive, proactive decisions to anticipated changes through structural measures, without considering farmers’ needs and established rules. Incorporation of indigenous practices and local knowledge contribute substantially to the rate of success and sustainability of adjustability decisions and actions, and hence flexibility. Failures in the modernization of traditional systems in Eritrea were caused by wrong estimates of design flood and scour depth (van Steenbergen et al., 2011a, 2011b, 2011c), as well as lack of consideration of existing rules and practices in design and operation (Mehari Haile et al., 2005a). Modernized systems are accused of enhancing unfair water distribution by favouring upstream farmers with more water access (Mehari Haile et al., 2011). However, when well managed, they provide minimum maintenance and routine work, allow flexible regulation and adopt hydraulically effective structures (Geleta, 2014).

Flexibility and real options used in traditional, improved traditional and modernized systems during a high flood event, are listed in Table 6.

4.2 | Low flood event

Low floods and river water levels in traditional spate systems lead to water scarcity conditions and hence to reductions of the irrigated area, deficit irrigation and low crop production. Dealing with low flows involves decisions on water allocation, distribution and size of area
to be irrigated. For example, farmers can decide to deal with low flows by diverting all available river water, prioritizing the upstream intake and area (van Steenbergen, 1997). Farmers tend to increase their options by augmenting available water through water harvesting and conjunctive use of shallow wells; change crop choice; share risks through sharecropping and digging small ditches to distribute water flow (redundancy).

In improved traditional systems, during low flows water managers are uncertain how much area can be irrigated and hence tend to adjust the irrigation plan. To spread the risk of water scarcity among farmers, in the GAS (Sudan) water managers introduced a lottery system to allocate fields who receive water first. In the next year the order of the water allocation is reversed. Similar adjustability measures in improved and traditional systems are taken at field level. For example the use of a lottery system to allocate actual irrigated area between farmers with priority given to unlucky farmers from last season (Fadul et al., 2019). One of the adjustability actions in the spate system around the Harosha river in Ethiopia is the construction of a bund to intercept low flood channels (Castelli et al., 2018).

In modernized systems, the concern of water managers during low floods is the reduced water diversion and uncertainty about the area that can be irrigated. During low floods, modernized systems are barely able to divert water through intakes due to the tendency of the main river channel to flow away from intakes (Hiben and Tesfa-Alem, 2014). Adjustability options to enhance flexibility may include seeking other water supply sources to supplement irrigation in addition to farmers’ measures at field level.

Flexibility and real options used in traditional, improved traditional and modernized systems during a low flood are described in Table 7.
4.3 Untimely flood event

In traditional systems, change in the starting date of the season results in great uncertainty about the extent and length of the flood duration period due to the implications for optimum cropping dates. Flexibility is provided through adjustable managerial decisions on handling the risk at field level and action to rebuild bunds that depend on the use of local materials such as trees, shrubs and soil to protect fields and bunds.

In an improved traditional system, with similar concerns of change and uncertainty, water managers adopt real actions for adjustability such as an emergency maintenance to the most critical structures and embankments and borrowing maintenance equipment from other collaborating agencies (cooperation) such as in the GAS (Fadul et al., 2018, 2019), and conjunctive use of groundwater as a supplementary source (redundancy). This option provided farmers in Wadi Zabid in Yemen with a substantial increase in irrigated area (van Steenbergen et al., 2010). Options for groundwater recharge provide linkage between spate irrigation and natural resources management (connectivity) such as in the Wadi Hadramout in Yemen as described by van Steenbergen et al. (2010).

In a well-managed modernized system decisions can be more sustainable with appreciable efforts of maintenance and preparation well before the expected season (slack) and conjunctive use of groundwater (redundancy). Provision of flexibility at farmer level is similar to other spate systems and related to managerial decisions such as change of crop.

Flexibility and real options used in traditional, improved traditional and modernized systems during untimely flood events are described in Table 8.

### Table 8: Flexibility and real options to cope with untimely floods in different types of spate irrigation systems

| Flexibility question | Flexibility characteristic features | Traditional system | Improved traditional system | Modernized system |
|----------------------|---------------------------------------|--------------------|-------------------------------|-------------------|
| 4. What needs to change or be adapted? | (g) Real options (strategy) | Decisions to modify cropping pattern or crop variety, reduce irrigated area, share risk. Actions to augment water (groundwater) | Decision to update the irrigation plan: divert water to easily accessed fields, reduce irrigated area, field preparation (summer tillage) | Actions to add water from alternative sources: shallow groundwater wells, maximize diversion from the river, recharge wells |
| | (h) Enablers | Farmers’ autonomy to choose crops and cropping pattern, availability of alternative water sources | Knowledgeable water managers and farmers willing to change plans | Availability of groundwater |

5 | Comparison of Flexibility in Spate Irrigation Systems

The results of flexibility assessment showed that traditional systems can cope with changes and avoid damage from destructive high flood peaks or untimely floods by selecting real options to rebuild or relocate intakes and
described by van Steenbergen (1997), the rate of modernized systems to their lack of flexibility, as well as the design water level and sediment trend. Alem (2014) compared traditional and modern spate systems in Tigray (Ethiopia). The authors attributed the damage and benefit to the system. Hiben and Tesfa-Alem (2014) compared traditional and modernized systems, in terms of flexibility of improved systems is relatively the best compared to traditional and modernized systems, while the impact on groundwater level can be reduced by groundwater recharge basins as practised in many countries.

Being considered the least flexible, modernized systems require high capital cost to implement real options such as constructing stilling basins to deal with sediment-laden flows during peak floods. However, in several countries the management of modernized systems lacks farmers’ involvement in decision making and proposed action, which has resulted in failures (Castelli et al., 2018). The requirements for resources for maintenance are often underestimated and the systems failed because of poor maintenance (van Steenbergen et al., 2010; Castelli et al., 2018). Low floods can be dealt with by reducing the irrigated area and adjustments in water-sharing rules. These options are only successful with farmers’ involvement in the decision process. Ignoring farmers’ input leads to a limited number of sustainable options for modernized systems to cope with low flood events. Therefore modernized systems are able to provide a more durable and sustainable irrigation system if managerial decisions are adjusted to include a participatory approach, also confirmed by a pilot study conducted by Castelli et al. (2018).

It can be observed from global experience that the flexibility of improved systems is relatively the best compared to traditional and modernized systems, in terms of the damage and benefit to the system. Hiben and Tesfa-Alem (2014) compared traditional and modern spate systems in Tigray (Ethiopia). The authors attributed the failure of the modernized system to underestimation of the design water level and sediment trend.

It is challenging to solidly attribute the high failure rate of modernized systems to their lack of flexibility, as described by van Steenbergen (1997), van Steenbergen et al. (2010), Oosterbaan (2010), Komakech et al. (2011), Mehari Haile et al. (2011), Hiben and Tesfa-Alem (2014), Libsekal et al. (2015) and Castelli and Bresci (2017). Limited knowledge of design and management of complex structures to handle unpredictable high floods with large sediment load and the poor use of traditional farmers’ knowledge may have contributed to the failure. Failure of some of the modernized systems around the world can be avoided by exploring adjustable managerial decisions that include farmers and a more participatory approach in the design, construction, maintenance and operation of the system. However, global experience shows that although modernized systems were effective in some cases, improved traditional systems were generally more effective. In fact, modernized systems can become more flexible by adapting operational plans to avoid peak flood diversion, improving rules for equal water distribution and, most importantly, involving farmers in decision making regarding operation and maintenance activities.

Comparison of the flexibility of different systems reveals that all spate irrigation systems can maintain flexibility by exploring and implementing a number of real options which could serve during the occurrence of risky events. However, promotion of flexibility in farming communities in spate irrigation is challenged by access to land and water resources, access to credit, tribal hierarchy and power structures, farmers’ participation and awareness, institutional arrangements, and technical and managerial capacity. Farmers and water managers can manage flood variability more successfully when a range of options or alternative paths are available. The framework provides a range of measures that integrate flood risk management (high, low and untimely) and irrigation development.

6 | CONCLUSION

Spate irrigation systems face a high level of uncertainty using an unpredictable water source from flash floods in ephemeral rivers. Flexibility is a key ingredient of coping strategies. In this paper we developed a conceptual framework to assess the flexibility of spate irrigation systems. The framework is based on earlier work by Difrancesco and Tullos (2015) and Anvarifara et al. (2016) applied to three types of spate irrigation system: traditional, improved traditional and modernized systems.

The conceptual framework serves as a professional guide for policy makers, water managers, WUAs and farmers to make a preliminary evaluation of their system, and explore goals, capabilities and options available. For policy makers, they will be able to determine the level of investment they need to make to achieve sustainability and prosperity for the livelihoods of spate irrigation communities. For water managers, they will be able to assess different options available, constraints and limitations for development and enhancement. For example, if a certain system lacks slack, then provision of access to fuse...
plugs, freeboard or a natural drainage system could be explored in a proactive manner. Similarly, farmers will be able to explore different options to go further for implementation.

It is beyond the scope of this paper to quantify the flexibility of the three system types. This could be done by quantifying the subfeatures describing the capabilities as shown by Difrancesco and Tullos (2015) to compare system types and prioritize potential options (Gupta & Goyal, 1989).

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