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# System-wide nexus analyses: water distribution rules, agricultural productivity and livelihoods in flood-based livelihood systems

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## Research Paper

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## Abstract

Water management and distribution rules in flood-based livelihood systems (FBLS) have a key role in enhancing system-wide productivity and livelihoods. While such potential has to a certain extent been harnessed in DG Khan FBLS in Pakistan, it has not yet been fulfilled in the Tana River and Fogera FBLS in Kenya and Ethiopia, respectively. These three systems are considered among the major sources of water and food security in their respective regions by the local governments and communities. Drawing from 105 individual interviews with Pakistani FBLS farmers, the paper establishes that a package of water management and distribution rules have significantly contributed to (a) mitigating excessive upstream floodwater use, (b) reducing downstream water scarcity and (c) realizing nearly 4 tons ha$^{-1}$ harvest of the major wheat crop across the upstream and downstream areas. This yield is about 20% higher than the country-wide average, and two-third of the maximum achievable. Furthermore, 86% of the upstream and three in four of the downstream farmers have managed to cover their livelihood needs that included health, school, housing, transportation, energy and food expenses. On the other hand, the analyses based on individual interviews with 94 and 147 FBLS farmers from Kenya and Ethiopia respectively, uncovered the negative consequences of the absence of a comprehensive package of water management and distribution rules. In Kenya, the downstream small-scale farmers that account for two-third of the Tana River FBLS population frequently suffer from floodwater scarcity. They could not cultivate the high return rice crop and their staple maize yield was low at about 1.25 tons ha$^{-1}$ or 20% of the maximum attainable. Four in five reported poor livelihoods. The upstream large-scale farmers however often diverted excessive floodwater; over 90% usually grow rice as well as maize as a second crop for home consumption. The situation in Fogera is similar. The water distribution rules prioritized the upstream rice cultivation introduced a decade back to boost economic growth. This, as informed by 95% of the interviewed farmers, has caused downstream floodwater scarcity, about 30% maize yield reduction and livelihood deterioration. These findings on the impacts of water distribution rules can contribute to formulating investments that better achieve the productivity and livelihood potentials of FBLS across Africa and globally.

## Introduction

Flood-based livelihood systems (FBLS) are large-scale water harvesting systems which make productive use of floods that are otherwise inherently unreliable in timing and volume and often destructive in nature (Zenebe *et al.*, 2022). FBLS cover 25 million hectares across water-stressed drylands in Africa and Asia, potentially providing water and food security for 50 million farmers and pastoralists (Puertas *et al.*, 2015). The systems also deliver several environmental benefits including recharging groundwater, reducing soil moisture and soil fertility depletion (Berg *et al.*, 2017).

For FBLS to function effectively, a comprehensive package of water distribution rules facilitating adequate system-wide (from upstream to downstream) floodwater allocation and minimizing floodwater damage and losses is needed. While this potential of water distribution rules has, to a certain extent, been harnessed in some FBLS in Asia, it has not yet been fulfilled in FBLS in Africa (van Steenbergen *et al.*, 2016).

Unlike in perennial irrigation systems, regular irrigation schedules with fixed intervals and amounts are not possible in FBLS due to the highly unreliable nature of floods. Water distribution rules serve as operational rules and make FBLS functional by creating some order and predictability in floodwater sharing and defining who gets water first, how much and who is next.

Water distribution and management rules have received limited research focus and have also been largely passed over in FBLS investment programs. The few studies that discuss water management and governance (Mehari *et al.*, 2007; Castelli *et al.*, 2018; Zenebe *et al.*,

2022) mainly focus on documenting water distribution rules and analyzing their effectiveness in mitigating the unpredictability of floodwater. They do not adequately analyze the 'nexus' between water distribution rules on the one hand, and agricultural productivity and livelihoods on the other. As well summarized by van Steenbergen *et al.* (2016), discussions on water management practices and rules in FBLS have often mainly covered general principles (transparency, accountability and participation), conflict resolution and prevention. In this paper we seek to advance scientific understanding on the positive and negative impacts of various sets of water distribution rules on system-wide floodwater supply, agricultural productivity and livelihoods. Analyses are based on three case studies that jointly cover the three major types of FBLS: (1) floodplain agriculture: cultivation of flood plains using either receding and/or rising floodwater, (2) spate irrigation: diversion, distribution and management of short duration flood flows from seasonal or ephemeral rivers and (3) flood inundation system: canals fed by temporary high water levels in rivers irrigate adjacent low-lying fields (Kool *et al.*, 2017).

Further to its scientific significance, the system-wide analysis is imperative from a development perspective as there is increasing interest to invest into FBLS. For instance, the Kenyan government has a plan to develop 50,000 ha in the period 2020–2025 (Zenebe *et al.*, 2022). The World Bank have prepared some 20 million USD 5-yr investment across the FBLS in Sudan, which is expected to be implemented as soon as conducive local conditions are established (MoIWR, 2021). The European Union has approved 40 million euros for the development of the Balochistan FBLS in Pakistan, to be implemented from 2022 to 2026 (European Union, 2021). The large majority of the few implemented investment programs in FBLS so far, particularly those in Africa, have largely been infrastructure-driven and did not adequately deliver on their promise to improve productivity and livelihoods (Mehari *et al.*, 2011; Libsekal and Mehari, 2020). The purpose of this paper is to demonstrate that such promise could be better realized if the investments recognize improving water distribution rules as imperative contributing factors and accordingly allocate sufficient financial and technical resources.

## Materials and methods

### *Case study descriptions*

The key features of the three selected case studies are summarized in Table 1. They present relevant situations for the system-wide impact analyses of different sets of water distribution rules and their enforcement arrangements:

- The many centuries old DG Khan spate irrigation system is located in the DG Khan district of the Punjab province in Pakistan (Fig. 1). It is endowed with a comprehensive set of water distribution rules that among others delineate the areas entitled for floodwater, determine the sequence and frequency of irrigation of these delineated areas, mitigate excessive upstream use and protect downstream rights. The spate irrigation system also has effective institutional arrangement anchored on the collaboration between the local government and the farmers' organizations.
- The 400 yr old flood inundation Tana River system is practiced in the Tana River county located in the Kenyan coast (Fig. 1). In this system, only upstream prioritizing water distribution rules are functional. The institutional set-up is also weak: there are no farmer organizations with system-wide outreach and the local government is yet to be actively engaged.
- The 200 yr old Fogera floodplain agriculture is located in the Fogera district of the Amhara region in Ethiopia (Fig. 1). The recent upstream rice cultivation in the floodplain resulted in the modification of the traditional water distribution rules that doubled the entitlement and further strengthened the upstream floodwater control and significantly diminished the downstream floodwater supply.

**Table 1.** Key characteristics of the three case studies

| | Case studies | | |
|---|---|---|---|
| Key characteristics | DG Khan spate irrigation, Pakistan | Fogera floodplain, Ethiopia | Tana River flood inundation, Kenya |
| Beneficiary groups | Farmers, pastoralists | Farmers, pastoralists | Farmers, pastoralists |
| Average household size | 10 | 4 | 4 |
| Household farm size in hectares | | | |
| Small-scale | 1–2 | 0.1–0.5 | 0.1–0.5 |
| Large-scale | 2–30 | 0.5–3 | 0.5–3 |
| Approximate irrigated area in hectares | | | |
| Potential | 114,000 | 40,000 | 95,000 |
| Under cultivation | 95,175 | 15,000 | 23,000 |
| Field water management structures | Gabion, concrete intakes | Earthen bunds | Earthen bunds |
| Climate: mean monthly temperature range (°C) | 25–34 | 20–30 | 23–38 |
| Climate: average annual rainfall (mm) | Below 200 | Below 400 | Below 300 |
| Soils | Silty clay loam | Silty loam | Silty loam |
| Major crops include | Wheat, sorghum, beans | Rice, maize, teff | Rice, maize |

*Source*: Own compilation based on Nederveen *et al.* (2011); Gebey *et al.* (2012); Khan *et al.* (2014); Zenebe *et al.* (2022).

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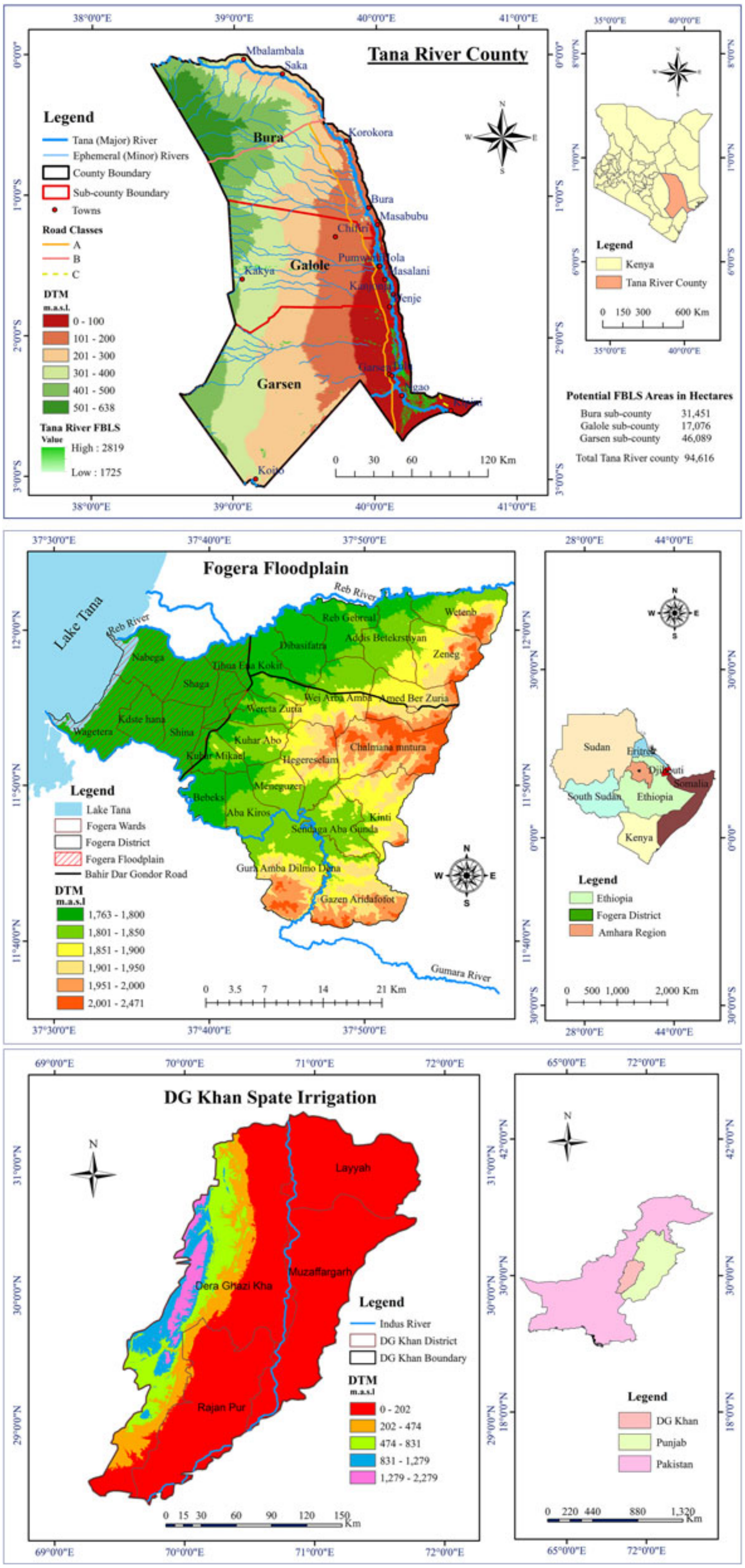


**Fig. 1.** Location maps of the three case studies: Tana River, Fogera and DG Khan FBLS in Kenya, Ethiopia and Pakistan, respectively.

There are several reasons for why DG Khan has a comprehensive set of water distribution rules. It has existed for centuries longer than the Fogera floodplain and the Tana River flood inundation system, and it has also been subjected to a number of interventions from development actors and the scientific community. These interventions have contributed to infrastructural improvement, formulations and modifications of water distribution rules. More recently, following the devastating floods of

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2010, innovative floodwater resilient structures such as permeable spillways and new gabion and stone re-enforced guide bunds and field intakes were constructed. Alongside this, the water distribution rules system was re-discussed, rationalized and updated (van Steenbergen *et al.*, 2016).

The annually irrigated areas in Table 1 correspond to the most frequent average flood season that occurs in 4 out of 5 yr (Khan *et al.*, 2014; Zenebe *et al.*, 2022). At 83% of the potential irrigable land, the annually irrigated area in DG Khan is much higher than that in Fogera floodplain and Tana River, which are respectively estimated at 37.5 and 24%. The main contributing factor is the fact that DG Khan has a comprehensive set of water distribution rules while upstream first is the only major operational rule in the other two systems. As indicated above, DG Khan also benefited from several investments that introduced more robust floodwater supply canal networks and floodwater management structures.

## Methods for data and information gathering

Qualitative and quantitative data and information was gathered through focus group discussions (FGDs) and individual interviews, respectively conducted with representative samples of the farming communities across the three FBLS case studies (Table 1).

### Individual interviews

In Fogera floodplain and Tana River, 94 and 147 representative farmers were selected for individual interviews using stratified random sampling. The selection was made from the databases of the Fogera Bureau of Agriculture and the Tana River Department of Agriculture and Livestock that consisted of 798 and 1757 farmers, respectively, with at least 10-yr experience in FBLS. As detailed in Table 2, all the major small- and large-scale farmer categories are equally represented, and the sample sizes are proportional to their respective total populations in the databases.

In DG Khan, 105 individual interview participants were identified through extensive stakeholder consultations undertaken (MetaMeta, 2021). The 105 respondents consisted of 21, 35 and 49 upstream, midstream and downstream farmers (roughly 50% are small scale) that fulfilled three criteria: (1) at least 10 yr uninterrupted engagement in FBLS; (2) good understanding of the operational water distribution rules, floodwater management and farming practices and (3) willingness to work together with the research and program team in documenting household income and expenses. It is important to note here that many farmers do not keep a good record and are often reluctant to provide household cash flow data.

The individual interviews complemented and gave depth to the FGDs by generating relevant quantitative data such as the percentage of farmers who ranked water distribution rules among the top factors that impact agricultural productivity and livelihoods; the system-wide crop yields; the net farming household incomes and livelihood statuses under different sets of water distribution rules. These and the related data were gathered through a questionnaire with a series of interconnected questions designed to harness individual perspectives on two or more interrelated issues. For example, the following were among the questions that captured quantitative information on the level of impact of water distribution rules on agricultural productivity and livelihoods: (1) which of the following factors impact your agricultural productivity and livelihoods: (a) availability and affordability of agricultural inputs (fertilizer, seeds, etc.), (b) access to finance, (c) market access, (d) water distribution rules, (e) water logging, (f) pests and diseases, (g) any other factors; (2) can you rank these factors starting with the one that has the highest impact? (3) Can you explain your ranking?

**Table 2.** Breakdown of individually interviewed Fogera floodplain and Tana River farmers

| Farmer categories | Total database population | Representative Sample |
|---|---|---|
| 1. *Fogera floodplain, Ethiopia* | *798* | *94* |
| Small-scale upstream rice farmers | 153 | 18 |
| Large-scale upstream rice farmers | 279 | 33 |
| Small-scale downstream teff and maize farmers | 176 | 21 |
| Large-scale downstream teff and maize farmers | 190 | 22 |
| 2. *Tana River farmer categories* | *1757* | *147* |
| Small-scale upstream rice and maize farmers | 145 | 12 |
| Large-scale upstream rice and maize farmers | 193 | 16 |
| Small-scale midstream rice and maize farmers | 131 | 11 |
| Large-scale midstream rice and maize farmers | 189 | 16 |
| Small-scale downstream maize farmers | 956 | 80 |
| Large-scale downstream maize farmers | 143 | 12 |

The sample sizes of each farmer category are proportional to their respective populations.

### Focus group discussion

Purposive sampling was employed to ensure the engagement of those knowledgeable about the operational water distribution rules and who have some 10-yr experience in FBLS. In both Tana River and DG Khan, 48 farmers equally representing the small- and large-scale upstream, midstream and downstream areas participated in six FGDs. In the Fogera, four FGDs were conducted with 32 respondents equally representing the small- and large-scale upstream and downstream farmers.

Each of the 16 FGDs conducted had eight homogenous members in terms of: (a) location of their farms (upstream, midstream and downstream)—this affects the degree of access to adequate floodwater supply; and (b) size of their irrigable areas—small-scale farmers often have limited financial resources to invest into better floodwater management and farming practices such as timely operation and maintenance (O&M) and adequate soil fertility management. Having such homogenous groups that share similar challenges and opportunities facilitates candid and inclusive public interactions (Smithson, 2000; Cassell and Symon, 2004).

The main purpose of the FGDs was to generate an in-depth understanding of water distribution rules and their enforcement mechanisms as well as the collective perspectives of the participating farmers on the level of impact of the rules on agricultural productivity and livelihoods. The FGDs were conducted in three sessions. The introductory session (20–25 min) acquainted and made the

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**Table 3.** Key water distribution rules in DG Khan FBLS in Pakistan described during the FGDs and confirmed to be operational by all individually interviewed farmers

| Rule on | Objective and description |
|---|---|
| Entitlement to floodwater | Only defined and mapped canals, structures and fields are entitled to receive floodwater supply |
| Irrigation depth and turns | Upstream area has priority to a single turn of a maximum of 500 to 1000 mm irrigation depth, and can get a second turn only after all other entitled fields are irrigated once |
| Special crop preferences | Wheat followed by sorghum have floodwater priority |
| Small and large floods | Upstream fields have priority for small floods (5–15 $m^3 s^{-1}$), midstream fields for medium floods (15–25 $m^3 s^{-1}$) and downstream fields for large floods (>25 $m^3 s^{-1}$). Small floods have no strength to reach mid- and downstream areas while large floods will cause damage in the upstream section. The flood discharges are estimated using velocity-area method in the tertiary or secondary canals that directly supply floodwater to the irrigated fields (van Steenbergen *et al.*, 2010) |
| Maintenance | The rule on maintenance stipulates that, given the unreliable and destructive nature of floods, maintenance should be taken very seriously. Accordingly, hefty penalties are enforced to start with and those who repeatedly (three or more times) fail to contribute through labor or in cash are deprived of floodwater supply altogether |

participants comfortable with the main purpose of the FGD. Using post-it cards, half of the participants were asked to outline the key currently operational water distribution rules indicating whether these rules are positively or negatively affecting their floodwater supply and harvests. The other half shared the most imperative water distribution rules that were operational in the past explaining why these are no longer operational. The cards were displayed in a large paperboard and the outlined points were further elaborated. The second roughly an hour-long session focused on detailed discussion guided by eight to ten guiding questions that systematically harness the history and content, implementation and impacts of key water distribution rules. This session was carefully moderated to ensure active engagement of all focus group members. In the third 20 min long session, each participant shared any additional thoughts in a couple of minutes and the moderator then concluded the FGDs with highlights of the major issues discussed and agreed upon.

### *Data analysis*

The qualitative FGD data were analyzed using the three-stage process of the 'thematic method' (Braun and Clarke, 2006; Nowell *et al.*, 2017): observation during data collection; data familiarization (reading through the text and listening to audio recordings); searching for themes—taking a much deeper look at the data to identify patterns and eventually themes. The three key themes that emerged were: various packages of water distribution rules; institutional enforcement arrangements and infrastructural settings; impacts of these two aspects on agricultural productivity and livelihoods. These themes were complemented and further elaborated during the individual interviews. Descriptive statistics and frequency criteria guided the analyses of the individual interview data that was systematically organized in a spreadsheet.

## Results and discussion

### *Floodwater management and distribution*

#### *Findings and analyses from the target case studies*

Floodwater management in DG Khan spate irrigation system is guided by a set of formally documented key water distribution rules (Table 3). These rules have been instrumental in curtailing excessive upstream floodwater diversion, reducing flood damage, safeguarding downstream water supply and facilitating timely O&M. The fields entitled to irrigation are defined and mapped. The farmers cannot increase the size of their delineated irrigated areas even if there are excessive floods. The upstream priority is limited to a single turn of about 1000 mm irrigation depth from small floods. The large floods that often cause damage in the upstream section are allowed to travel to the downstream cultivable land where they are more easily harnessed for productive use.

There is a functional collaborative institutional arrangement between the local government (Irrigation Department) and community-level Water Users' Associations (WUAs). The local government is more actively involved in the upstream areas where there is not a well-established WUA to ensure that the water distribution rules are observed and there is no excessive upstream floodwater use (Fig. 2). In the midstream and downstream areas this responsibility is largely fulfilled by the respective WUAs with the support of the local government.

The Irrigation Department has experienced technical staff who oversee O&M needs. They receive funding through government budget allocations and contributions from the farming communities. The general arrangement is that the farming and herding communities cover 60% of the routine O&M costs such as silt and weed clearance (in cash, labor or both) and 10–20% of major infrastructural repair or new developments. The adequately implemented O&M activities have contributed to several environmental benefits including mitigation of floodwater damage to agricultural land, enhanced soil moisture retention and decreased soil fertility depletion. The priority crops are wheat and sorghum, followed by beans. New crops will not be entitled to floodwater supply unless their introduction has been discussed and agreed upon among the Irrigation Department and the WUAs.

The floodwater management situation in the Tana River flood inundation system is sharply different. The only operational *upstream first rule* gives absolute priority to the upstream irrigating farmers. The rule does not specify the irrigation depth and turns—the upstream decide when the floodwater should flow to the downstream predominantly small-scale farmers that account for about two-third of the farming population. Rules on small and large floods, crop preferences and those that facilitate O&M are non-existent in Tana River. The institutional arrangement is also weak. Unlike in the DG Khan system there are no full-fledged WUAs but field-level committees of 20–30 farmers exist that manage floodwater sharing along the same field canal. Several of these field-level committees are not active—nearly two-third, about half and a third of the interviewed upstream, midstream and downstream farmers respectively never participated in their respective committee meetings (Fig. 3).


| | Local Government | Community (Water User Association, WUA) | Tribal Leaders | Local Government and Community (WUA) | Local Government and Tribal Leaders | All Three Institutions |
|---|---|---|---|---|---|---|
| Upstream Farmers % | 5% | 19% | 5% | 62% | 0% | 10% |
| Midstream farmers % | 6% | 49% | 3% | 34% | 3% | 6% |
| Downstream farmers % | 4% | 45% | 8% | 33% | 0% | 10% |

**Fig. 2.** Perceived responsibility per farmer group about the institutional responsibility for managing floodwater distribution in DG Khan spate irrigation system in Pakistan.
*Source*: Individual interviews.

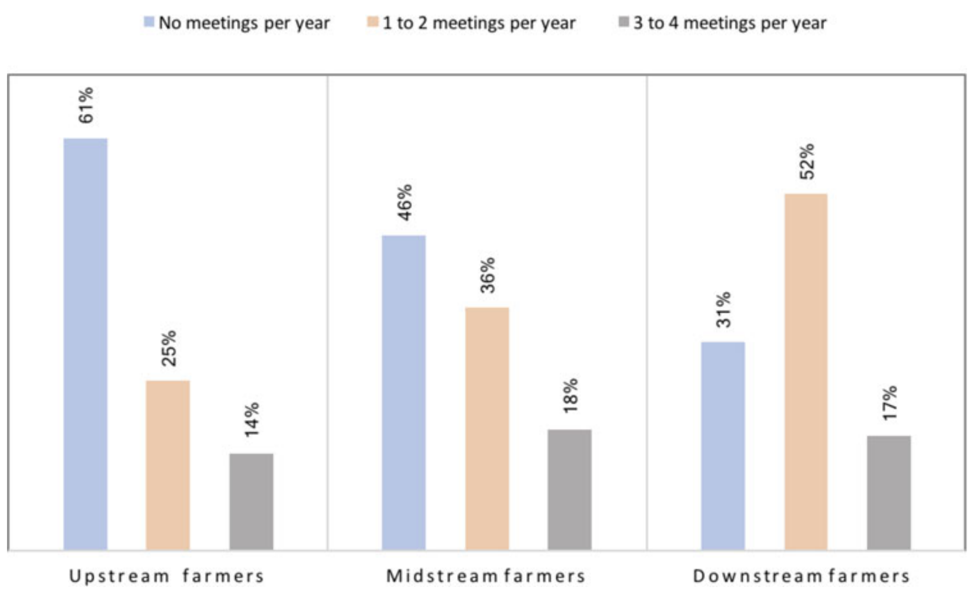


**Fig. 3.** Level of engagement of the Tana River flood-dependent farmers in irrigation committees. Usually, the committees convene four times annually.
*Source*: Individual interviews.

The lack of institutional maturity in Tana River despite being twice as old system as Fogera can be attributed to three factors. First, unlike in Fogera, there have not been any major external interventions that facilitated or motivated farmers to organize themselves. Government authorities largely ignored Tana River FBLS as they considered it a marginal agricultural system. Secondly, small-scale farmers have more pressing issues, such as ensuring sufficient harvest to feed their families. Finally, the large-scale farmers did not see the urgency to organize themselves as they have not been as severely affected by floodwater scarcity as the small-scale farmers.

In Fogera floodplain, the floodwater management is mainly governed by the *upstream first rule*, but unlike in the Tana River, the rule defines the irrigation depth and turn. Prior to the introduction of upstream commercial rice, a decade back by the local government, the rule granted the then maize and teff upstream farmers the priority for a single irrigation turn of 350 mm depth, and a second turn only after all the other fields secure the same single turn. This upstream priority irrigation depth was doubled following the introduction of rice to meet the high irrigation demand of the crop, estimated at 1000 mm for Fogera rice varieties (FAO, 2019). As a result, floodwater supply to the now downstream maize and teff crops has reduced by about 50%.

There is a strong functional institutional arrangement in the Fogera floodplain built on long-term collaboration between water-masters (farmer leaders) highly respected by the community and a legally powerful local administration. This collaborative engagement supported with hefty, yet graduated sanctions, has achieved a high degree of enforcement of the upstream first rule and successfully facilitated wide

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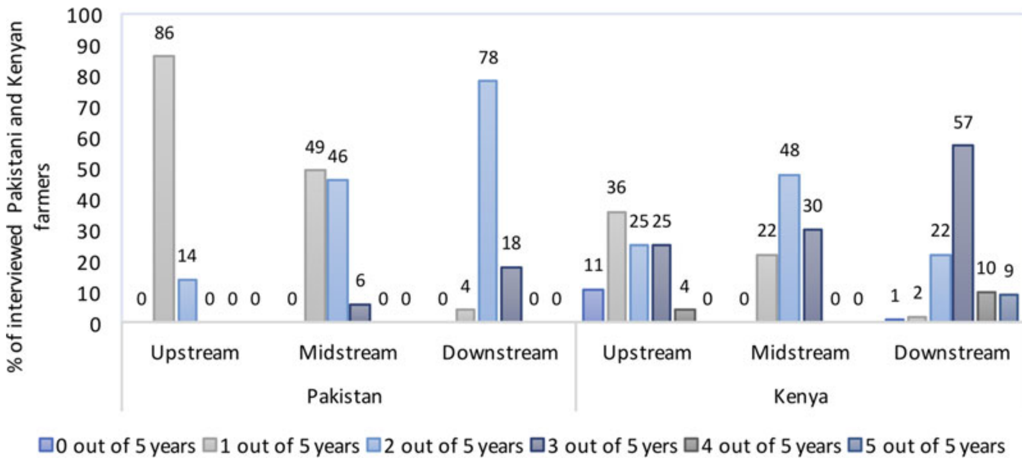


**Fig. 4.** Comparative assessment of floodwater scarcity experienced by Pakistani and Kenyan farmers in the past 5 flood season years when floodwater has not been physically limiting.
*Source*: Interview data.

participation of the farming community in collective O&M activities. The water-masters are empowered and legally supported by the local administration to sanction first and second time violations of the upstream first rule or for failure to contribute to O&M by fines of 10 and 25 euros, respectively. Repetitive offenses could lead to deprivation of floodwater supply. A group of three to five water-masters represent 200–600 farmers in their respective villages. They do not receive salary, but in recognition of their service, they are entitled to priority irrigation.

The comprehensiveness of the water distribution rules and the strength of the enforcing institutions can explain the significantly better system-wide water distribution in DG Khan (Fig. 4). As gathered from the individual interviews, nearly 57% of the Tana River downstream farmers experienced water scarcity in 3 out of 5 yr when floodwater supply was not physically limiting—the corresponding value in DG Khan was 18%. Moreover, 10% of the Tana River downstream farmers did not have access to adequate floodwater supply in 4 out of 5 yr and 9% throughout the 5-yr period.

The relatively low floodwater scarcity condition in DG Khan is particularly significant given the fact that the flood-irrigated areas in the downstream (651 ha) and the midstream (722 ha) are nearly triple that in the upstream (260 ha) (Fig. 5). Both upstream and midstream farmers occasionally divert large floods in violation of the rule on 'small and large floods'. However, large floods are less destructive and can be more successfully harnessed midstream, explaining why midstream farmers manage to irrigate the highest share (85%) of total available land.

### *Complementary analyses from other FBLS*

While scientific studies are limited, there are some documented cases that further illustrate the above presented impacts of water distribution rules and institutional arrangements on floodwater management and distribution. Below we provide four relevant examples.

The first example concerns Wadi Mawr spate irrigation system in Yemen. The predominant upstream first rule combined with the absence of demarcation and crop preference rules (Table 3) encouraged upstream expansion of the profitable, but highly water demanding banana plantation resulting in significant downstream floodwater supply reduction (Zenebe *et al.*, 2016).

In the second example, the Wadi Siham spate irrigation system in Yemen, there is a 'rule on small and large floods' as defined in Table 3.

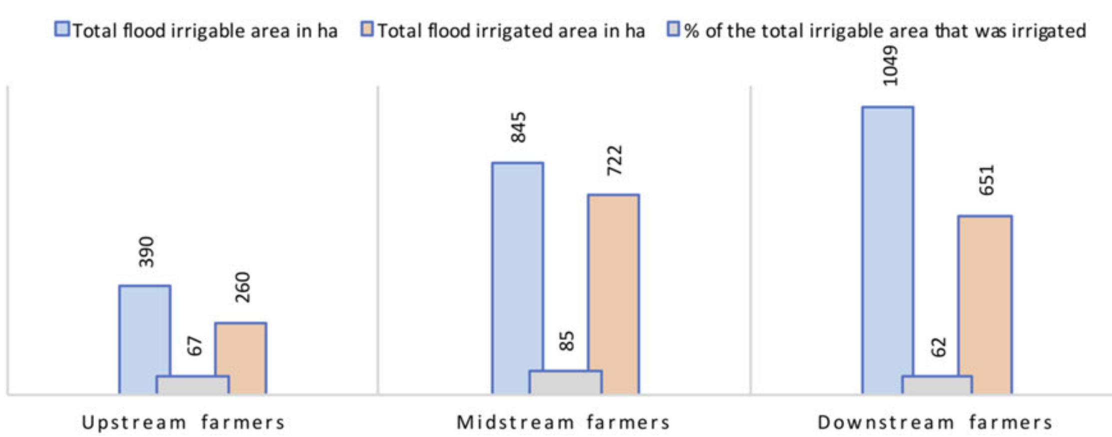


**Fig. 5.** Comparison of system-wide (upstream to downstream) flood irrigated areas in the DG Khan spate irrigation scheme in Pakistan. The data were gathered in 2021 and according to the interviewed farmers the irrigated area values are representative of the situation in the most frequent average flood season that occurs in 4 out of 5 yr.
*Source*: Individual interviews.

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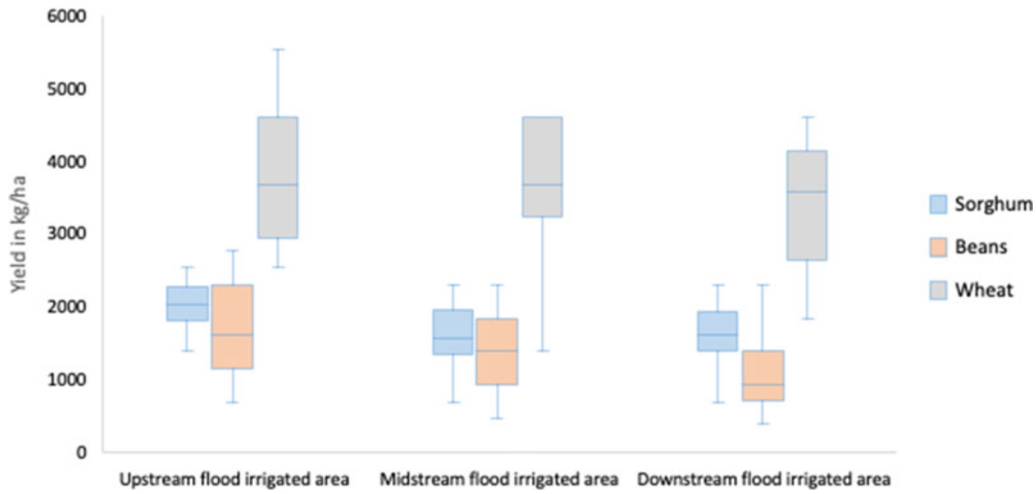


**Fig. 6.** Boxplot of the system-wide (upstream to downstream) productivity of the major crops in DG Khan spate irrigation system. The median, the line cutting across the box, is the center value of the database. The lower and upper edges of the box display the yields higher than a quarter and three quarters of the dataset while the highest and lowest data-points of the whiskers (lines) represent the maximum and minimum yields respectively.
*Source*: Interview data.

Following modernization intervention, the multiple offtake system that allowed downstream water users to withdraw water directly from the wadi was replaced with a single upstream concrete distribution offtake. This gave more physical floodwater control to the upstream and led to frequent violation of the rule depriving the downstream of large floods (Mehari *et al.*, 2007). As in Tana River, the Wadi Siham downstream farmers are not organized into WUAs and do not have adequate institutional capacity to collectively safeguard their floodwater supply entitlement (van Steenbergen *et al.*, 2010). DG Khan has a markedly different experience and situation than Wadi Siham. Infrastructural improvement interventions resulted in a multiple offtake system and the downstream receive their floodwater supply through direct diversion from the ephemeral river system. They do not hence rely on upstream canals and structures. The downstream farmers are well organized while the government (Irrigation Department) actively supports enforcement of water distribution rules. As a result, the downstream floodwater entitlements are largely respected.

Thirdly, Malota and Mchenga (2020) extensively discuss, albeit on a qualitative basis, that introducing a comprehensive set of water distribution rules is critical to address the upstream–downstream floodwater sharing challenges in the Malawi Shire Valley flood recession agriculture.

Finally, Shah *et al.* (2002) confirm that collaborative institutional arrangements between farmers and irrigation agencies (this is the case in DG Khan and Fogera) often result in effective water management systems, as: (a) usually, neither the farmers nor the irrigation agencies are on their own capable of meeting the financial resources required for O&M; and (b) farmers alone often do not invest into long-term sustainability of irrigation systems—a role that can be fulfilled by the public institutions.

## *Agricultural productivity*

### *Findings and analyses from the target case studies*

The majority of the interviewed farmers across the three target case studies identified water management and distribution rules as having significant impact on their crop productivity.

In the DG Khan spate irrigation system, nearly 70% of the upstream and midstream farmers and about 80% of the downstream farmers ranked the key set of water distribution rules (Table 3) as the second most important factor contributing to their crop productivity, after physical floodwater availability. Agricultural inputs came a distant third followed by lack of adequate financial capacities to, for instance, timely cultivate the irrigable land; soil degradation; water logging and salinity problems.

The crop yield data collected in 2021 from the 105 interviewed DG Khan farmers are displayed in Figure 6. As confirmed during the individual interviews and FGDs, 2021 was characterized as an average flood season with a 4 in 5 yr occurrence. Figure 6 illustrates the positive impact of the water distribution rules on system-wide crop productivity: (a) the median upstream and midstream wheat yields are basically the same and that of the downstream is only 5% less; and (b) the midstream and downstream sorghum farmers each managed nearly 80% of the upstream farmers' median yield. This is a significant achievement given the skewed distribution of flood-irrigated areas (see Fig. 5).

In the case of beans, the upstream–downstream median yield difference is very significant at about 43%, and moreover downstream farmers are concentrated on the lower yield range (Fig. 6). Beans are grown as a second crop after either wheat or sorghum harvests. The field bund heights in DG Khan are about 1 m and while some downstream farmers receive one full irrigation turn (1000 mm), most manage about 750 mm. Midstream fields receive 1000 mm while most upstream fields harness some 1500 mm. The net irrigation requirement of wheat and sorghum is about 550 mm while that of beans is 300 mm (FAO, 2020). Therefore, after the wheat or sorghum irrigation demands are satisfied, there will be sufficient residual moisture for bean production in the upstream and midstream areas, but a deficit of at least 100 mm or about a third of the demand in the downstream. Beans are sensitive to water stress. Field experiments conducted in arid and semi-arid regions found that a 25% irrigation deficit resulted in an average 30% beans yield reduction (Rai *et al.*, 2020).

Although median yields of the DG Khan spate-irrigated fields are higher than the country-wide average by about 20% (wheat),

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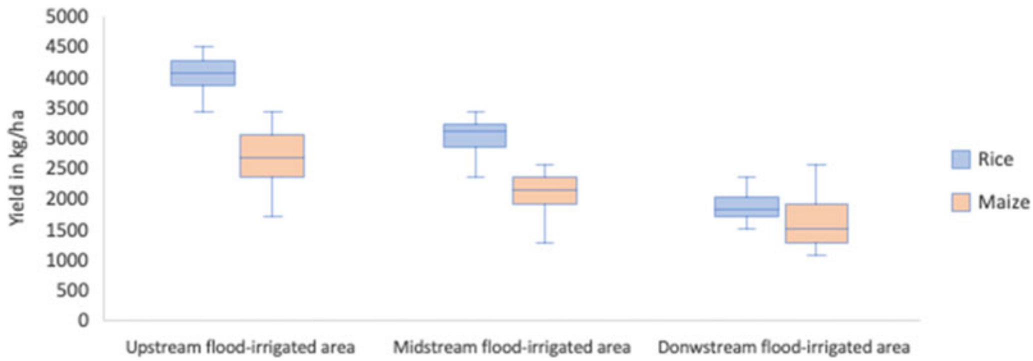


**Fig. 7.** Boxplot of the system-wide (upstream to downstream) productivity of the major crops under Tana River flood inundation system. The median, the line dividing the box, is the midpoint value of the yield dataset. The lower and upper margins of the box represent the yields higher than 25 and 75% of the dataset. The top and bottom values of the whiskers are the maximum and minimum yields.
*Source*: Interview data.

60–70% (sorghum) and 40–60% (beans); they are about two-thirds of the 3500 (wheat) and 6000 kg ha$^{-1}$ (sorghum) maximum yields obtained when irrigation and farming practices are not limiting (FAO, 2019). This yield gap is not primarily caused by floodwater supply scarcity, but rather due to impurity of seeds, poor land preparation and weed management and insufficient fertilizer application. Even if we assume a quarter of the 750–1000 mm irrigation depth received by downstream fields is lost due to flood damage to field intakes or breaching of field bunds, the wheat and sorghum water requirements would still be adequately met. The deep silty loam soils have a high water holding and capillary capacity making soil moisture readily available to the sorghum and wheat roots which grow to well below 1.5 m depth (Mehari *et al*., 2008).

In Tana River, the system-wide agricultural productivity gap is significantly bigger than that in DG Khan. Upstream median rice yield is higher by a third and two-thirds as compared to the midstream and downstream, respectively (Fig. 7). Likewise, upstream maize productivity is nearly 20 and 44% higher than the respective midstream and downstream yields, respectively. Primarily due to inadequate floodwater supply, just a quarter of the downstream managed to cultivate the high irrigation demanding rice crop and they mainly produced maize to cover their household needs. By contrast, nearly two-thirds and four in five of the midstream and upstream farmers harvested rice for commercial purposes and maize as the second crop for home consumption.

All the interviewed Tana River downstream farmers attributed their poor harvests to the upstream first water distribution rule—the only operational rule—that empowers the upstream to divert as much floodwater as they want. This view is shared by 40% of the midstream farmers. On the other hand, nearly all the upstream farmers and 60% of the midstream farmers identified inadequate field water management structures as the major limiting factors for agricultural productivity. This very problem is also acknowledged by nearly half of the downstream farmers. Unlike in DG Khan where gabion or concrete re-enforced flood resilient field water distribution intakes are in operation (van Steenbergen, 1997; Mehari *et al*., 2005), Tana River farmers rely on earthen structures that are more frequently susceptible to flood damage resulting in substantial floodwater losses.

The acute floodwater supply shortage faced by the downstream Tana River farmers is reflected in the rice yield of a quarter of the maximum attainable 9000 kg ha$^{-1}$ (FAO, 2019). That said, the best harvest by the upstream Tana farmers that often enjoy 1500 mm irrigation depth (rice requires 1000 mm) is also just 50% of the maximum achievable value. This is mainly due to significant floodwater losses. Moreover, nearly 40% of the interviewed upstream farmers reported pests and diseases incidences. This most probably is caused by excessive flooding and prolonged wet conditions as the problem is reported by only 3 and 5% of the midstream and downstream farmers, respectively. Finally, inadequate farming practices could have played a role. Tana River farmers practice direct broadcast sowing, which results in high planting density, low germination rate and poor seed setting (Zenebe *et al*., 2022). Field experiments conducted in several perennial irrigation systems in Kenya (Ndiiri *et al*., 2013) and in Mali FBLS (Traore *et al*., 2020) established that a farming system that combines transplanting of younger seedlings and wider spacing can increase rice productivity by up to 40%. As Tana River FBLS has not been subject to any internal or external improvement interventions—neither improved field water management structures nor better farming practices have been introduced.

In Fogera floodplain, nearly all (95%) of the interviewed downstream farmers explained that the modified upstream first rule that doubled the priority entitlement of the upstream rice cultivation to two irrigation turns (about 700 mm) is the main factor for the decline of their teff and maize yields by approximately 15 and 33%, respectively (Fig. 8). Under the modified rule, the farmers explained that receiving a single turn (about 350 mm) is their best-case scenario. This irrigation depth, if efficiently utilized, would be sufficient for teff, but it is far below the maize requirement estimated at 650 mm (FAO, 2020).

The median maize productivity under the traditional water distribution rule when the downstream fields often managed two turns (Fig. 8) was also low at about 64 and 55% of the corresponding Ethiopia country average (4327 kg ha$^{-1}$) and maximum (6000 kg ha$^{-1}$) attainable yields (Cochrane and Bekele, 2018; FAO, 2020). The significant, up to 40% floodwater losses, reported by farmers due to frequent flood damage to the weak earthen field water distribution structures, is the main contributing factor here. The intervention in Fogera that introduced upstream rice cultivation did not invest into gabion or concrete re-enforced field water management structures.

The median upstream Fogera rice yield is about 20% lower than that in the Tana River FBLS (Figs. 7 and 8). This is largely because unlike in the Tana River, the upstream first rule in Fogera limits the rice fields' priority irrigation to 700 mm, which is 30% below the optimum requirement. In addition, the Fogera rice productivity shares the two main challenges faced in


**Fig. 8.** Boxplot of system-wide (upstream to downstream) productivity of the Fogera floodplain major crops under the traditional (pre-rice era) and the modified (post-rice period) water distribution rule. The median, the line dissecting the box, divides the yield dataset into two equal parts. The lower and upper edges of the box display the yields greater than 25 and 75% of the dataset while the whiskers indicate the minimum and maximum yields respectively.
*Source*: Interview data.

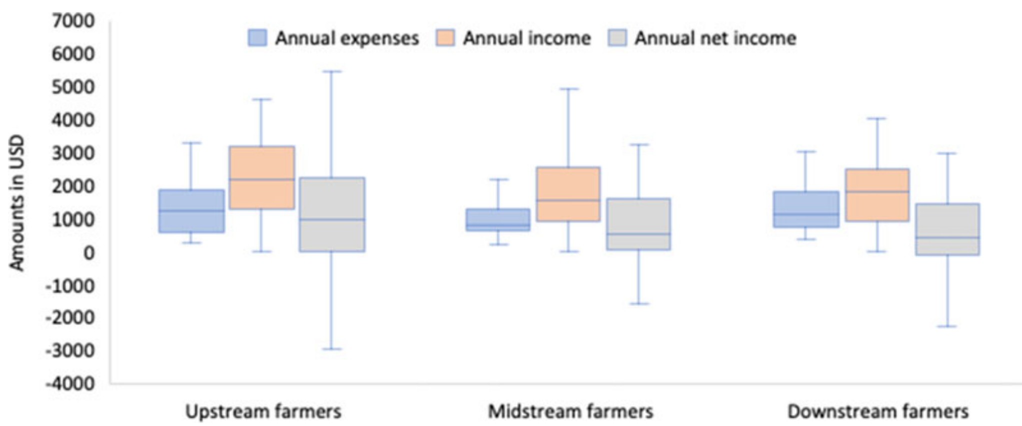


**Fig. 9.** Boxplot of DG Khan farmers' household expenses and incomes analyses. The median (the line cutting across the box) represents the midpoint value of the dataset. The lower and upper boundaries of the box display the expenses and incomes greater than 25 and 75% of the dataset. The lowest and highest whiskers (lines) are the minimum and maximum expenses and incomes respectively.
*Source*: Interview data.

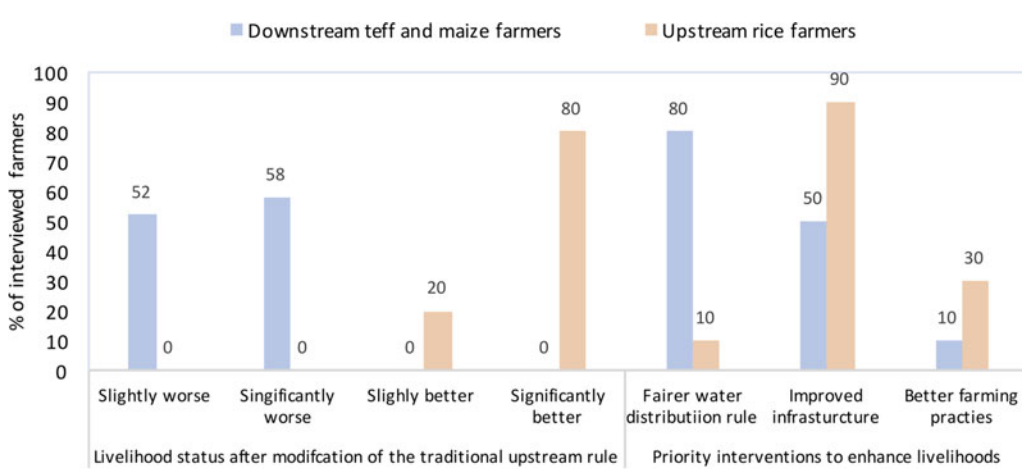


**Fig. 10.** Ethiopian Fogera farmers' perspectives on the livelihood impact of the modification of the traditional upstream rule following the introduction of rice and the priority interventions that could improve their living standards.
*Source*: Interview data.

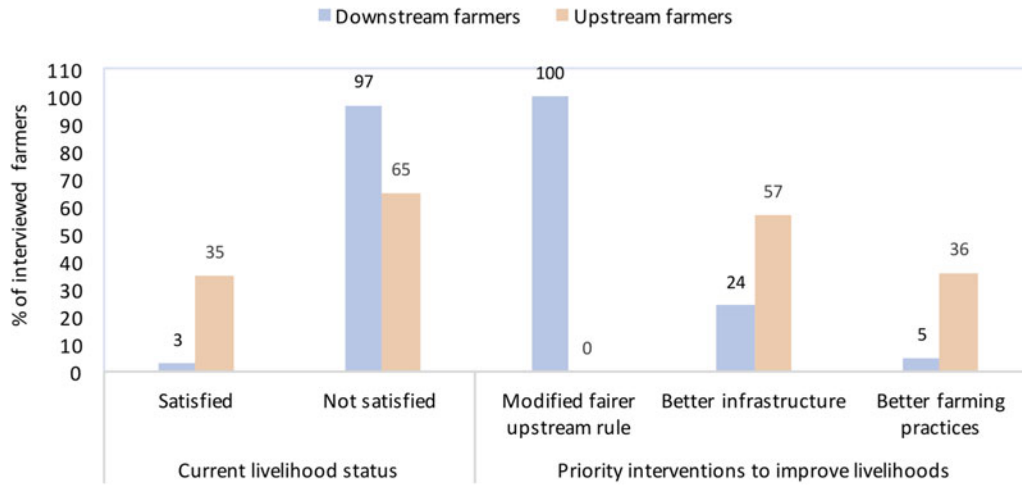


**Fig. 11.** Tana River, Kenya farmers' views on their current livelihood status and the priority interventions that could improve their living standards. *Source*: Interview data.

Tana River: (1) substantial floodwater losses; and (2) the non-optimal direct broadcast sowing-based farming system.

### *Complementary analyses from other FBLS*

The upstream favoring water distribution rules that curtailed downstream floodwater supply across the earlier discussed Wadi Mawr and Wadi Siham cases also resulted in significant negative impacts on agricultural productivity.

Wadi Mawr spate irrigation system embodies the challenges of both Tana River (predominantly upstream first rule) and Fogera (upstream expansion of high-water demanding crop). The combined effect was that the downstream area became confined to subsistence sorghum cultivation characterized by frequent crop failures (Mehari *et al*., 2011; van Steenbergen *et al*., 2016). In Wadi Siham, despite the existence of the rule on 'small and large floods', the upstream farmers are irrigating as much as they want as is the case in Tana River. As a result, the downstream sorghum productivity fluctuates between 500 and 1000 kg ha$^{-1}$ (van Steenbergen *et al*., 2010).

## Livelihood analyses

The data gathered from the 105 interviewed DG Khan farmers (Fig. 9) established that 86, 80 and 76% of the upstream, midstream and downstream farmers managed to meet their household livelihood needs that included health, school, housing, transportation, energy and food. Crop production was the main source of livelihood, generating respectively 67, 53 and 58% of total income. The key set of water distribution rules (Table 3) that facilitated comparable system-wide crop productivity (see Sections 'Floodwater management and distribution' and 'Agricultural productivity') underpin the narrow gap between the percentages of upstream, midstream and downstream farmers who adequately met their livelihood needs.

In Fogera and Tana River, reliable household expense and income data are not available, but farmers qualitatively reflected on the nexus between their livelihoods and water distribution rules in response to the questions: (1) If and how have downstream Fogera teff and maize farmers' livelihoods been impacted following the modification of the traditional water distribution rule? (2) Are the upstream and downstream Tana River farmers satisfied with their current level of livelihoods? (3) What, if any, are the recommended Fogera and Tana River farmers' priority interventions for improving their living standards?

The modified upstream first rule, which doubled the upstream rice cultivation floodwater supply to 700 mm, features prominently as the main contributor for the significant deterioration of the Fogera downstream farmers' livelihoods (Fig. 10). The overwhelming majority (80%) of these downstream farmers informed that reverting to the fairer traditional upstream rule is critical for boosting their harvests and enhancing their livelihoods.

This desire to return to the traditional rule may not, however, be possible as it could result in significant rice yield reductions. There are two other potential options:

- Land redistribution that allows the downstream farmers to also have some upstream plots. The government owns all land in Ethiopia and this option can legally be implemented, and
- annual rotation of the two-turn priority irrigation and rice cultivation between the upstream and downstream. If supported by the local government, this option can become operational as it will most likely be backed by the water-masters (farmer leaders) who overwhelmingly prefer the traditional water distribution rule.

Nearly all the Tana River downstream farmers are also not satisfied with their current living standard, which they unanimously attribute to the presently operational rule that grants the upstream limitless access to floodwater (Fig. 11). For their livelihoods to be improved, the Tana River downstream farmers who participated in the FGDs informed that it is critical to introduce water distribution rules that facilitate more equitable sharing of the 3-month flood season (April–June) between the upstream and the downstream.

## Conclusion

This paper undertook system-wide analyses of the nexus between water distribution rules, agricultural productivity and livelihoods in FBLS based on data gathered from 474 farmers across three cases studies: (a) DG Khan in Pakistan with a comprehensive set of water distribution rules that largely balance the competing upstream and downstream floodwater demands; (b) Fogera in Ethiopia, where there is only one operational rule that gives the

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upstream absolute priority for a single 350 mm irrigation turn and (c) Tana River in Kenya, which is mainly governed by a water distribution rule that grants upstream farmers unrestricted access to floodwater.

These differences in the comprehensiveness of the water distribution rules have contributed to significant differences in floodwater security. While nearly 60% of the Tana River downstream farmers experienced water scarcity in 3 out of 5 yr when floodwater supply was not physically limiting—the corresponding value in DG Khan was 20%. In Fogera, the rule modification to cater for the high water demanding upstream rice cultivation, resulted in 50% floodwater supply reduction to the downstream maize cultivated area.

The relatively more equitable floodwater distribution in DG Khan ensured that the downstream wheat and sorghum harvest was at least 80% of that of the upstream farmers. The DG Khan yields were also 20% (wheat) and 60% (sorghum and beans) higher than the country-wide averages. By contrast, the downstream Tana River farmers' productivity was half that of their upstream neighbors while the overall rice and maize yields were 40 and 55% less than the respective country averages. As to Fogera, the upstream-favoring modification of the water distribution rule resulted in 30% downstream maize yield reduction.

The weak earthen structures in both Fogera and Tana River could also have further reduced agricultural productivity as some of the floodwater that reaches the downstream may be lost and hence not be available for the crops. The weak institutional arrangement in Tana River may have also played a role in the poor downstream agricultural productivity. As is the case in Fogera, stronger institutional arrangements could have limited the upstream water right to two turns. Currently, the Tana River upstream farmers are irrigating as much as they want.

Livelihoods were closely correlated to the varied system-wide floodwater accessibilities and agricultural productivities. Narrow gaps in income were found for DG Khan farmers even though the downstream- and midstream-irrigated areas were triple that of the upstream. The Tana River downstream farmers reported poor livelihood status, which they attributed to the upstream first rule. The living standard of all consulted Fogera downstream farmers deteriorated following the modification of the water distribution that doubled the upstream floodwater supply entitlement.

Finally, investment attention to FBLS across Africa and Asia is increasing but still being directed at the 'physical infrastructure'. The findings of the paper indicate that for these investments to better realize their often-stated goal of enhancing agricultural productivity and livelihoods; they should embrace 'water distribution rules improvement' as important intervention area that merits as adequate financial and technical resources as the physical infrastructure.

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