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Rebound Effects in Irrigated Agriculture in Uzbekistan: A Stakeholder-Based Assessment

Ahmad Hamidov [1,2,*], Ulan Kasymov [3], Kakhramon Djumaboev [4] and Carsten Paul [1]

[1] Research Area 3 "Agricultural Landscape Systems", Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany; carsten.paul@zalf.de
[2] Department of Irrigation and Melioration, "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers (TIIAME)" National Research University ("TIIAME" NRU), 39 Kary-Niyaziy Street, Tashkent 100000, Uzbekistan
[3] Chair of Ecosystem Services, International Institute Zittau, Technische Universität Dresden (TUD), Markt 23, 02763 Zittau, Germany; ulan.kasymov@tu-dresden.de
[4] Regional Representative Office for Central Asia, International Water Management Institute (IWMI), Apartment 120, House 6, Osiyo Street, Tashkent 100000, Uzbekistan; k.djumaboev@cgiar.org
* Correspondence: ahmad.hamidov@zalf.de; Tel.: +49-33-4328-2166

Abstract: There is wide consensus among scholars and practitioners that improved irrigation technologies increase farm productivity and improve resource use efficiency. However, there is also growing empirical evidence that efficiency improvements in irrigation water use may create rebound effects, i.e., they may trigger changes in farmers' behavior that partly or fully offset the technical water savings expected under *ceteris paribus* conditions. In extreme cases, total water consumption may even increase. We studied the impacts of introducing water-saving irrigation technologies in Uzbekistan and used structured stakeholder interviews for an expert-based assessment of potential rebound effects. Our findings contribute to the understanding of impacts of technological and institutional responses to environmental and economic pressures in sustaining water resources. The study demonstrates that although the objective of increasing irrigation efficiency may be achieved, the actual water savings under Uzbek conditions are likely to be reduced due to rebound effects. Unless there are effective policy interventions, we expect rebound effects through an increase in water supply for crops that compensates for current shortages of irrigation water availability, an increase in irrigated area, a switch to more water-intensive crops, and overall economic growth. The findings of this paper provide a reference point for estimating the water-saving potential and for evaluating and adapting policies.

Keywords: water-saving technology; sustainability; irrigation efficiency; Central Asia; water–energy–food nexus

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1. Introduction

Worldwide, there is a consensus among policymakers, experts, and scholars that the use of advanced irrigation technologies may increase both farm productivity and resource use efficiency. Efficiency improvements are often considered a key technological solution to meet increasing demands for water due to agricultural intensification, industrial development, and population growth, exacerbated by climate change and the associated pressures on natural ecosystems [1]. However, there is also growing empirical evidence that efficiency improvements in irrigation water use may come with rebound effects—adaptive changes in farmer and consumer behavior that offset all or part of the intended resource savings [2]. In extreme cases, total water consumption may even increase [3,4]. Rebound effects are quantified as the share of resource savings from adopting a technical innovation that would be expected in a *ceteris paribus* situation, but that does not manifest due to behavioral changes of relevant stakeholders [2].

In Uzbekistan's semiarid zones, water is a vital natural resource. Irrigated agriculture plays a significant role in the country's economy, comprising 30% of the overall gross domestic product (GDP) [5]. The annual water demand of all sectors of the economy was amounted at 56 km^3 in 2019 [6], but the actual water withdrawal was 20% less than the required amount [7]. In fact, since 2005 the country receives on average 85% of total required water during normal years, whereas during dry years (e.g., in 2008 and 2011) it receives about 70–75% of the total annual required water [7]. Alarmingly, water availability has been decreasing due to climate change, population increases, and inefficiencies in water use and management. Due to the unsustainable use of water from the Amudarya and Syrdarya rivers for irrigation (they were diverted into cotton fields during the Soviet period, i.e., 1920–1991), the level of the Aral Sea, which is fed by the two rivers, was reduced by 29 m from 53 m in 1960 to 24 m in 2018 [8,9]. Furthermore, the water volume decreased by more than 90%, i.e., from 1080 km^3 in 1960 to 71.3 km^3 in 2018 [7]. Environmental and human health in the areas close to the sea has deteriorated. Over 50% of irrigated fields suffer from soil salinization, mainly due to poor management of the drainage system [10]. Residents exhibit higher rates of asthma, cancer, and increased infant mortality due to environmental pollution [11,12].

It has been reported that excessive water losses, low irrigation efficiencies, waterlogging, and widespread soil salinization have caused a decline in crop yields and agricultural crop productivity [13]. Much irrigation infrastructure is in disrepair due primarily to a lack of investment and poorly functioning irrigation facilities (e.g., seepage from broken canals and ineffective irrigation management). As a result, irrigation water losses in agriculture are very high (currently estimated at 37%). This includes the loss of water during transportation to the fields [14]. Recent studies estimate that water loss in eight water consumer associations (WCAs) in Kashkadarya Province of Uzbekistan amounted to 40–45% [15]. In Bukhara Province, Hamidov et al. [16] found a water loss of 20% at the main canals and a loss of 35% at the secondary and tertiary canals, which were managed by WCAs.

Responding to these challenges, Uzbekistan's government has developed and implemented policies in 2013 and 2019 that promote water-saving irrigation technologies. The impact of these policy interventions is to be seen in the future. Although improving the efficiency of irrigation infrastructure reduces water losses at the field level, resulting water savings at the watershed/basin level are usually much smaller [17], with negative implications for water availability in natural ecosystems, such as the Aral Sea. On the one hand, water lost at the field level may in fact not be lost at the watershed level, since a part of it will re-enter streams and shallow groundwater aquifers as return flows [18,19]. On the other hand, rebound effects are likely to occur as farmers adapt their behavior to the higher efficiencies, increasing their water use to optimize their economic returns [2]. As a matter of fact, there is already anecdotal evidence that farmers have increased their lands in the areas where water-saving irrigation technologies were installed.

Although rebound effects and Jevons' paradox are well documented for efficiency improvements in agricultural irrigation [3,4], case studies typically focus on measurement-based ex-post analyses, precluding preventive measures in the form of adapted policies [17,20]. Where ex-ante studies exist [21,22], they rely on data-intensive modelling. To our knowledge, no study has yet been published that conducts ex-ante analyses of irrigation-related rebound effects in world regions with limited data availability. Our study addresses this research gap by proposing a novel approach that utilizes expert interviews for an ex-ante assessment of rebound effects. The objective of our study is to assess the likelihood of direct rebound effects and of economy-wide rebound effects associated with a planned improvement of irrigation efficiency. We use Uzbekistan as a test case, representing a country where water scarcity poses severe challenges for natural ecosystems and future development, where strong improvements in irrigation efficiency are planned at a national scale, and where limited data availability precludes the use of model-based approaches for estimating rebound effects. In the following section, we describe our case study area, rebound mechanisms in the context of irrigated agriculture, and our method for stakeholder involvement. In Section 3 we present our findings, and the final section discusses the results and provides our conclusions.

2. Materials and Methods

2.1. Study Area and Policy Interventions

Rebound effects are typically evaluated based on measured or modelled data. However, as in most Central Asian republics, data availability and quality are critical issues in Uzbekistan. The level of uncertainty in reported or modeled irrigation water will exceed the effect sizes of water savings and rebound effects, especially during the early stages of a transforming irrigation infrastructure, where only small shares of the area benefit from the improved technology. Although the analysis of a long time series of assessments—conducted at a time when large percentages of the irrigated area have already switched to the new technology—could overcome this problem, information on potential rebound effects is most valuable at the early stages of the innovation process, where it enables policymakers to formulate adapted policies. To overcome data limitations, we employ an expert-based approach by inviting a group of Uzbek specialists to discuss the ongoing implementation of policies that promote the adoption of water-saving technologies (such as drip and sprinkler irrigation) across the country and evaluate four types of economic mechanisms that may lead to rebound effects.

Major water sector reforms in Uzbekistan began in 2003 with Decree No. 320 of the Cabinet Ministers of Uzbekistan, Improvement in the Organization of Water Resources Management [15]. A key element of the reform was creating a multilevel water management system made up of basin irrigation system authorities (BISAs), irrigation system authorities (ISAs), and WCAs. The main responsibilities of BISAs, which are funded by the state, are to manage all large-scale water infrastructures, including the effective use of water resources at the basin level. The main task of an ISA is to ensure timely and fair distribution of water resources to the local WCA [13]. The WCA is positioned to deliver services for its members (farmers) with water allocation and infrastructure maintenance. The WCA charges farmers an irrigation service fee (ISF), and most WCAs charge these on a per-hectare basis due to the lack of water metering devices on each farm. Under the Uzbek WCA bylaws, water consumers should fill out water request applications to receive irrigation water five days prior to the date the water is to be supplied [23]. However, the water supply depends on water availability, which usually changes from year to year and during the seasons. When water is scarce in a particular year, farmers' applications to irrigate secondary crops may be rejected by BISAs and local administrations. S1 in Supplementary Materials provides general information about the study area.

More recently, the Uzbek government launched incentive programs for farmers in 2013 (Decree No. 176 of the Cabinet of Ministers) and 2019 (Decree No. 4499 of the President) promoting water-saving irrigation technologies, such as drip and sprinkler irrigation. Although the initial program was rather declarative, the latest program has been practically implemented and is our study's focus. Within this program, the involved farmers are released from unified land taxes for five years and are permitted to cultivate secondary crops in the same vegetation period using saved water. As a result, drip irrigation technologies were installed on approximately 76,200 ha (2% of the total irrigated area) between 2013–2019; of these, 52,600 ha were for orchards and vineyards, 11,900 ha were for vegetables and melons, and 11,700 ha were for cotton. The technologies can also be implemented in areas with other crops, such as cereals. In 2019, water-saving irrigation technologies were newly installed on approximately 37,769 ha of land [24]. The program implementation aims to reduce water consumption and increase land productivity effectively (e.g., yield increases, reductions in production costs, and shortening of cotton harvesting period) and is planned to be expanded in the coming years. For instance, installing water-saving technologies on an additional 43,500 ha of irrigated land was planned for 2020 [24].

The installation of drip irrigation technologies has been subsidized by the government and local banks to increase adoption by farmers. The government subsidies cover 50% of the costs (approximately 800 Euro/ha), and the local banks finance the remaining 50% by providing low-interest credit to farmers for 3 years. Responding to reduced imports of agricultural products (e.g., sunflowers, soybeans, rice, and legumes) due to the COVID-19 situation in 2020, Uzbekistan's government plans to expand cultivated land areas to increase food production [25]. This also implies an increase in the total irrigated area.

By 2019, the government promoted water-saving irrigation technologies through subsidy programs in 12 provinces of Uzbekistan and the autonomous republic of Karakalpakistan. The transformation process is still in its early stages. Table 1 presents the scale of water-saving technologies implemented in 2019.

Table 1. Introduction of water-saving technologies in Uzbekistan in 2019 (for all crops).

Provinces	**Irrigated Land (1000 ha)**	**Water Consumption (km^3)**	**Technology Implemented Area (1000 ha)**	**Technology Implemented Area (%)**
Karakalpakstan	510.4	5.6	0.42	0.1
Andijan	264.5	2.5	2.32	0.9
Bukhara	274.6	3.0	1.19	0.4
Djizzakh	300.3	2.2	3.99	1.3
Kashkadarya	514.6	3.6	1.75	0.3
Navoiy	123.0	1.6	1.30	1.1
Namangan	283.2	2.3	3.03	1.1
Samarkand	379.6	2.5	7.64	2.0
Surkhandarya	287.1	2.6	4.27	1.5
Syrdarya	325.6	2.6	0.77	0.2
Tashkent	398.5	2.9	8.89	2.2
Ferghana	368.7	3.8	1.96	0.5
Khorezm	265.9	2.9	0.22	0.1
Total:	4296.0	37.9	37.77	0.9

Source: personal communication with an expert at the Ministry of Water Resources (MWR).

2.2. Rebound Effects in Irrigated Agriculture

Multiple studies around the world have reported rebound effects in irrigated agriculture. For example, in China the agricultural sector's water productivity has significantly increased over the last twenty years due to efficient irrigation technologies [26]. However, this has not resulted in a similar decline in total agricultural water use. The rebound effect was estimated at 61.49% between 1998 and 2014. The authors argue that "the expected water savings from efficiency improvement could be offset by increased water use for agricultural production growth due to technology enhancement" [26]. The rebound effect was also documented in Tunisia; despite introducing efficient technologies such as sprinklers and drip canal linings since 1995, the total crop water consumption increased and was 11% higher in 2006–2007 [27]. Moreover, in the US (Kansas), Pfeiffer and Lin [3] evaluated the effect of a conversion from traditional irrigation systems to higher efficiency systems (e.g., an incentive-based cost-share program to subsidize more efficient irrigation technology). However, the intended reduction in groundwater use did not occur. In fact, increased groundwater extraction was observed due to shifting crop patterns. For Morocco, Molle and Tanouti report that promotion of drip irrigation led to an expansion of cultivated areas, higher crop densities, and a shift to crop rotations with higher water demand [28]. For the Murray-Darling Basin in Australia, Wheeler et al. found that farmers who received subsidies for more efficient irrigation systems significantly increased their water consumption relative to farmers who did not receive such subsidies [29].

These examples highlight the risk of water-saving policy failures, as implementing water-saving technologies and improving irrigation productivity may not necessarily result in reduced water use. In most cases, rebound effects are detected only after implementing more efficient irrigation infrastructure. Policy responses to undo them are typically lacking because they could put severe pressure on farmers who invested into newly irrigated farmland or who have started to rely on more profitable crop rotations. Consequently, in the literature, the importance of preventing rebound effects through adequate water-saving policies is highlighted. These policies include limiting the total size of irrigated areas, reducing the total amount of water rights following efficiency improvements, or safeguarding that part of the achieved water savings is used for environmental goals [2].

2.2.1. Estimation of Rebound Effects

Rebound effects are defined as adaptive behavioral changes resulting from increases in resource use efficiency that partly or fully offset resource savings. From an engineering perspective, higher technical efficiencies automatically translate into lower resource use as humans continue their behavior as before (*ceteris paribus* assumption); this is not the case in real-world systems. Higher efficiencies may also change availability and costs of associated goods and services, and humans are bound to change their use and consumption accordingly. Where the availability of a resource had been lower than demand, a part of the resource savings is likely to be used to satisfy the demand. Where lower costs increase profit margins, producers will be motivated to expand their production. Where consumer prices fall, consumers will be motivated to consume more or substitute cheaper products with more expensive ones of higher quality [2].

For example, a more efficient irrigation system can irrigate the same area with less water. If the water availability before the innovation has been lower than water demand, farmers are likely to use part of the saved water to meet crop requirements. Furthermore, economic considerations may motivate farmers to expand irrigated areas or to switch to more water-intensive and more profitable crops or crop rotations. Finally, in countries where irrigated agriculture is responsible for a relevant share of the GDP, more efficient irrigation systems may accelerate overall economic growth and create additional water demand from non-agricultural sectors. All this reduces the potential water savings. Figure 1 provides a schematic diagram to illustrate the rebound mechanisms analyzed in our study.

Rebound effects are quantified as the share of resource savings that an innovation would achieve under *ceteris paribus* conditions (i.e., if producers and consumers did not change their behavior), which does not materialize due to adaptations under real-life conditions. For example, if a more efficient irrigation system has the technical potential to reduce water use by 100 m^3, but real-life savings amount to only 70 m^3 due to changed water consumption, the rebound effect is 30%. If efficiency gains are fully offset by increased consumption and no water is saved, the rebound effect is 100%. Finally, if water consumption after the technical innovation is higher than before, the rebound effect is larger than 100%. This is referred to as Jevons' paradox [2].

2.2.2. Technical Potential for Water Savings through More Efficient Irrigation Systems

In Uzbekistan, the dominant form of irrigation is furrow irrigation. Changing to more efficient irrigation systems such as sprinkler irrigation or drip irrigation could reduce water requirements. The efficiency of an irrigation system is characterized by the ratio between the amount of water available to the plants and the amount of water used. Applying the default values provided by Berbel et al. [30], we characterized the efficiency of furrow irrigation systems as 60%, of sprinkler irrigation systems as 80%, and of drip irrigation systems as 95%. This means that under furrow irrigation, for 60 L reaching the plants, 100 L of water have to be used. Under sprinkler irrigation, only 75 L are required for the same effect, indicating a water-saving potential of 25% for a switch from furrow to sprinkler irrigation. Under drip irrigation, only 63 L are required, indicating a water-saving potential of 37% for a switch from furrow to drip irrigation.

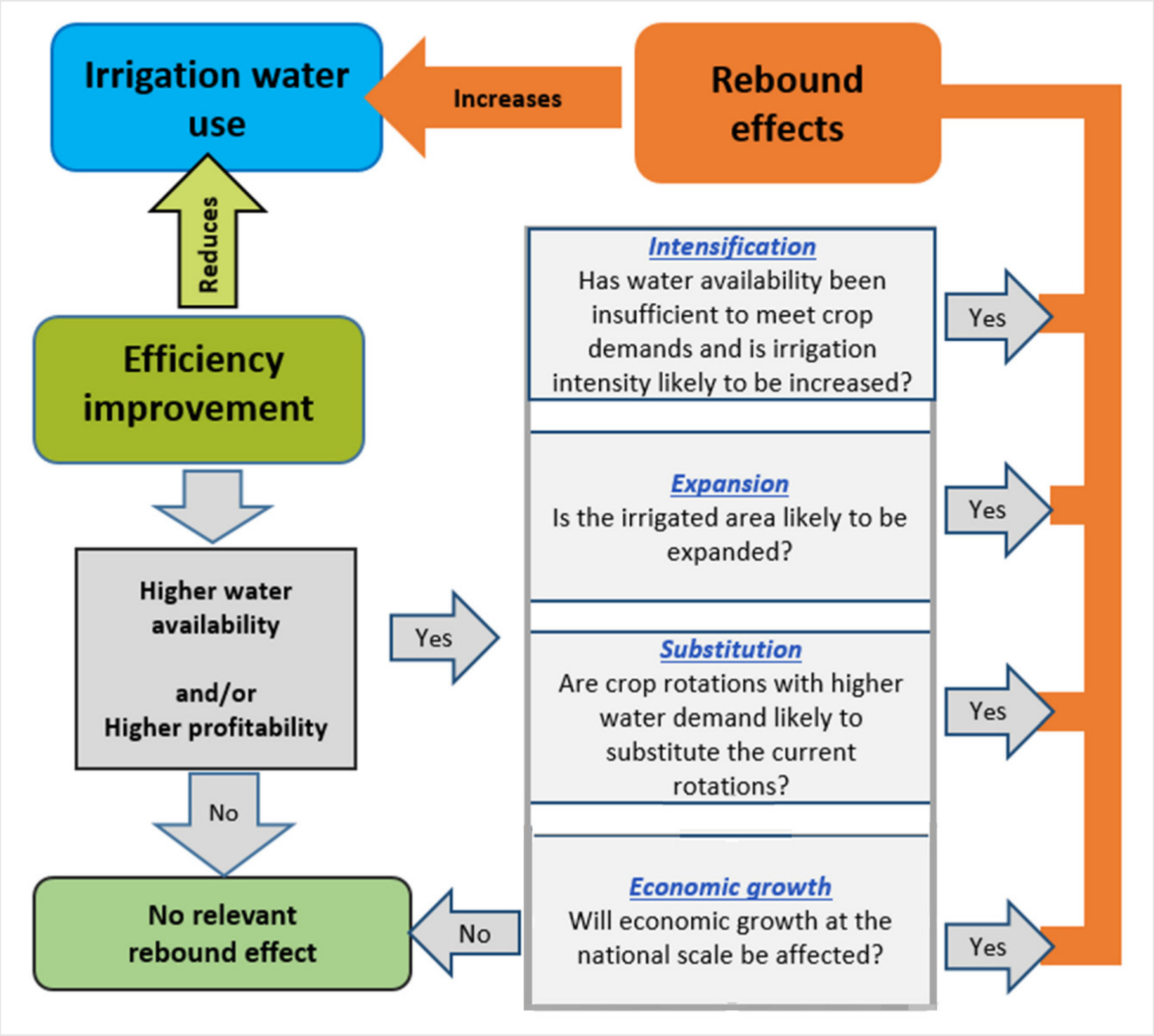

Figure 1. A schematic diagram of mechanisms that can cause rebound effects in the context of improved irrigation efficiency.

2.2.3. Expert-Based Assessment of Rebound Effects

Due to data limitations in Uzbekistan, assessments of rebound effects based on statistical data are not possible. Although data on actual water use is available, models that could reliably predict what water use would have been in the absence of innovations are lacking. To overcome these limitations, we use expert-assessment and two-stage structured interviews. In the interviews, we focus on economic rebound effects identified by Paul et al. [2], namely: (I) is production likely to be expanded? (II) Can the more efficient process be used to substitute other processes? (III) Will economic growth at the national scale be affected? Although rebound literature also describes indirect rebound effects, where monetary savings generated by using more efficient processes are re-spent on goods or services that themselves use the saved resource [31], we did not test for this in our study. Indirect rebound effects are not typical and/or difficult to consider in the context of agricultural water use [18], and may in our case be partly captured as part of economy-wide effects. Adapting the rebound mechanisms described above to the context of irrigation in Uzbekistan, we analyzed the likelihood of the following reactions to efficiency improvements:

(a) Increased irrigation to achieve full yield potential

We assume that water savings from technical innovation will first be used to satisfy existing demand. Where water shortages previously prevented farmers from irrigating according to crop requirements, farmers are likely to increase their irrigation once additional water becomes available through more efficient technologies.

(b) Increased irrigated area

More efficient irrigation systems can make it profitable for farmers to increase their irrigated area. Whether farmers may avail of this option depends on restrictions through policies and regulations and economic factors, such as access to land, capital, and markets.

(c) Switching to more water-intensive crops or crop rotations

With more efficient irrigation systems, it may be profitable for farmers to switch to more water-intensive crop rotations, including growing secondary or tertiary irrigated crops in a single year.

(d) Triggering overall economic growth

Economic activity is generally tied to resource use. Where innovation contributes to economic growth, it will also contribute to resource use in other sectors. Although the relationship between economic growth and water use is complex, we use resource use per GDP as a proxy to generate a rough estimate of this effect.

2.3. Expert Interviews

Expert-based assessments typically use small panels of stakeholders representing the required areas of expertise. In this study, the experts were selected on the basis of their expertise regarding water-saving irrigation technologies. The list includes leading specialists in the area of water use and management in Uzbekistan. For instance, TIIAME and the Ministry of Water Resources (including their provincial branches), as the key irrigation water organizations, were represented by seven experts. Most importantly, these experts were involved in the design and implementation process of the technology adoption. Furthermore, resource users involved in technology adoption in two different provinces of Uzbekistan contributed by sharing their practical expertise and experiences (S2 in Supplementary Materials).

Expert interviews involved a two-stage process. During the first stage, as part of an exploratory research stay, the authors visited two provinces in the Ferghana Valley (Ferghana and Andijan) and collected qualitative (four expert interviews: two farmers and two local water authorities) and quantitative secondary data (official statistics) in winter 2020. The authors then conducted 14 structured interviews with stakeholders representing research organizations, state agencies, donor communities, private consulting firms, and resource users in summer 2020. The second stage included the verification and discussion of our preliminary results with mostly the same Uzbek experts in summer 2021 (three experts from the first round could not be reached again and were replaced by new stakeholders). Due to the COVID-19 pandemic situation, all interviews in the summers of 2020 and 2021 were conducted using the Zoom online platform.

During the interviews, we provided information about the context of our research. We asked the interviewees to assess the potential effect size of the four economic mechanisms described above (S3 in Supplementary Materials). Additionally, we asked them to rate how certain they were about their respective answers, offering the choice between “uncertain,” “certain,” and “very certain.” This information was used to weigh their responses in our analysis. Answers that the interviewees felt certain about were counted once, whereas answers they felt very certain about were counted twice (doubled). Answers that the interviewees felt uncertain about were not considered in our evaluation. Finally, we evaluated the responses to assess the potential rebound effects of modernizing the irrigation infrastructure in Uzbekistan.

3. Results

The study findings strongly indicate that economic rebound effects are likely to occur in Uzbekistan in the future. The following expert assessments provide the basis for this statement.

A. Increased irrigation to achieve the potential yield

There was a strong agreement among experts that a deficit concerning irrigation water currently exists. Most interviewees quantified it as between 20% and 30% for the whole country, highlighting that it varies greatly between provinces and years (Figure 2). For instance, if the water deficit is approximately 5% in Tashkent Province, it can be approximately 30% in Syrdarya and Djizakh provinces. Furthermore, it was noted that the deficit was more than 30% in 2008 and 2021 in Uzbekistan. This was the reason why secondary crops were not cultivated during these dry years. Interviewed farmers complained that despite adopting water-saving irrigation technologies, water shortages during vegetation seasons (mainly during June–July) remain a major challenge for attaining yields.

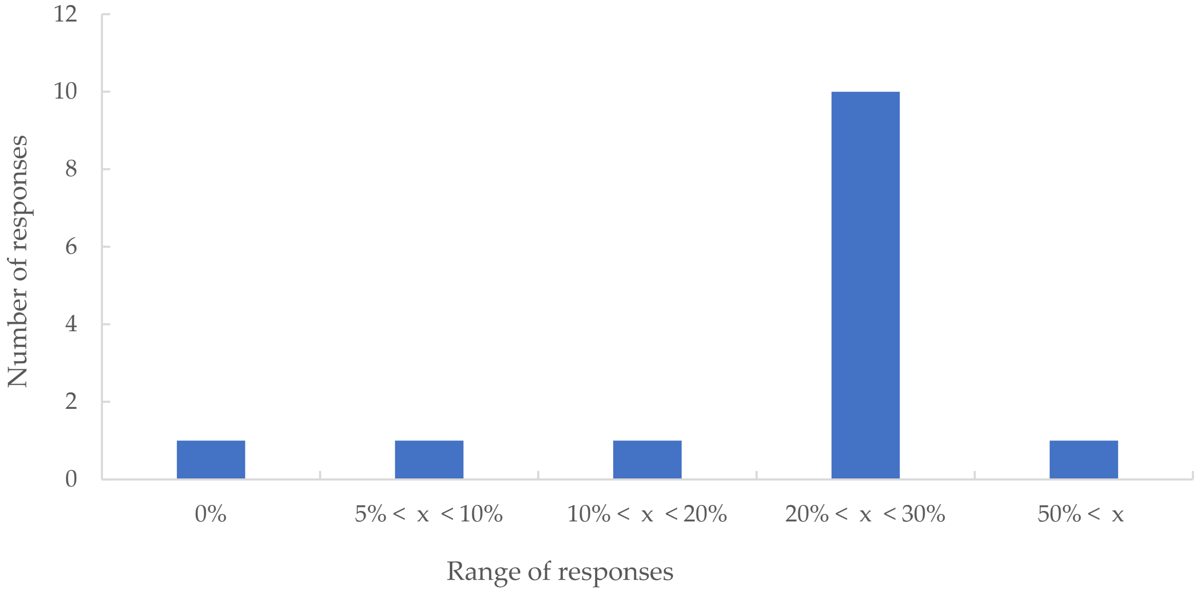

Figure 2. Irrigation water deficit for farmers. Histogram of experts' weighted responses to the questionnaire. Answers rated "very certain" by the respondents were counted twice (doubled), and answers rated "certain" were counted normally. Answers rated "uncertain" were not considered.

Water availability also depends on the state of the irrigation infrastructure. For example, the collapse of a major water reservoir in Syrdarya Province in 2020, where up to 1 km^3 of water was discharged, had a major impact on water availability. Moreover, there is currently weak water-use planning due to the difficulties in estimating current water demand. The experts noted that water-use plans (e.g., water allocation to WCAs) had been developed based on outdated Soviet methodologies, which results in unreliable information and planning. Figure 2 summarizes responses, where the majority of experts agree about irrigation water deficits in the country.

B. Increased irrigated area

Experts were far more divided when predicting the reaction of farmers to improved efficiencies in the irrigation infrastructure. As to what degree farmers would likely expand their area of irrigated fields, answers ranged from "no increase" up to "increases of 50%." The range chosen most frequently was from "0%" to "between 20% and 25%" (Figure 3). According to farmers' views, the adoption of water-saving irrigation technologies would most likely result in major land expansion (i.e., up to 50%). By contrast, other experts estimated from "no expansion" up to "increases of 15%". Some respondents noted that abandoned irrigated lands, which were used in the past, could be reclaimed again. This would, however, require the involvement and support of the state. The wide variation in responses might be because some respondents focused on the potential expansion in general. At the same time, others also considered whether farmers would initiate this expansion or whether the government would initiate such an expansion. There are currently some internal discussions among state agencies to increase irrigated lands by at least 500,000 ha (approximately 12%) due to improved irrigation technologies that are expected to save approximately 7 km^3 of water by 2030. In fact, agricultural land use has been expanded by about 300,000 ha (about 7%) between 2019 and 2021 through new lands or through abandoned lands restored as irrigated land. Respondents observed that the expansion had already taken place in the Narpay district of the Samarkand Province. The experts also identified the timeframe (i.e., 10–15 years) required for a potential expansion of the irrigated areas. The priority would be to increase water use efficiency at the farm level within the existing irrigated lands. If achieved, the potential expansion of irrigated lands could be envisioned as a next step. However, some experts were critical of the idea to expand irrigated lands, arguing that more attention is required for environmental and land productivity issues, such as soil health, crop rotations, control of groundwater, and salinity levels. Figure 3 illustrates the differences in the opinion of respondents.

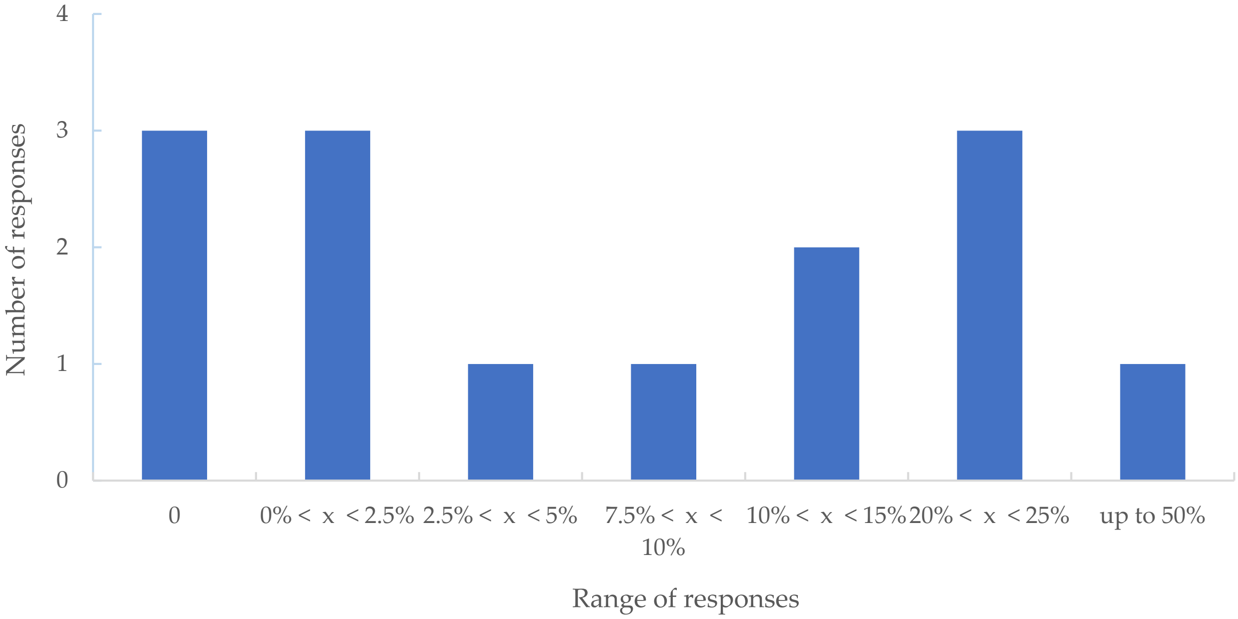

Figure 3. Expected expansion of irrigated area.

C. Switching to more water-intensive crops or crop rotations

For the question of whether farmers would likely switch to more water-intensive crops or crop rotations, and by how much the water demand would increase as a consequence, answers ranged from "no additional water demand" to "between 30% and 40% additional water demand" (Figure 4). The answer chosen most frequently was "0% additional water demand" because the respondents expected that the effects of implementing water-saving irrigation technologies would not be significant during the next 5–6 years. Decree No. 4919 from 11 December 2020 also highlights that water is deficit in Uzbekistan and that the amount of water available for irrigation will not be changed in the future even though farmers wish to plant new crops. Furthermore, farmers still need to fulfill the state quota for strategic crops (i.e., cotton and wheat). However, this might change in the longer term as the state has started to reduce its strategic crop interventions, allowing farmers to make decisions regarding crop rotation (e.g., water-intensive rice cultivation, vegetables and melons). This will also depend on market dynamics and demand for particular agricultural products. Under such scenarios, it is possible that water demand will increase, and farmers may use more irrigation and drainage water. For instance, farmers may rent out their lands to other users after cotton/wheat harvesting for secondary crop production. Most importantly, the state is currently encouraging farmers to cultivate secondary crops to address food insecurity concerns during the COVID-19 situation. It was noted that the increase in water demand could be prevented by introducing water limitation mechanisms in the future.

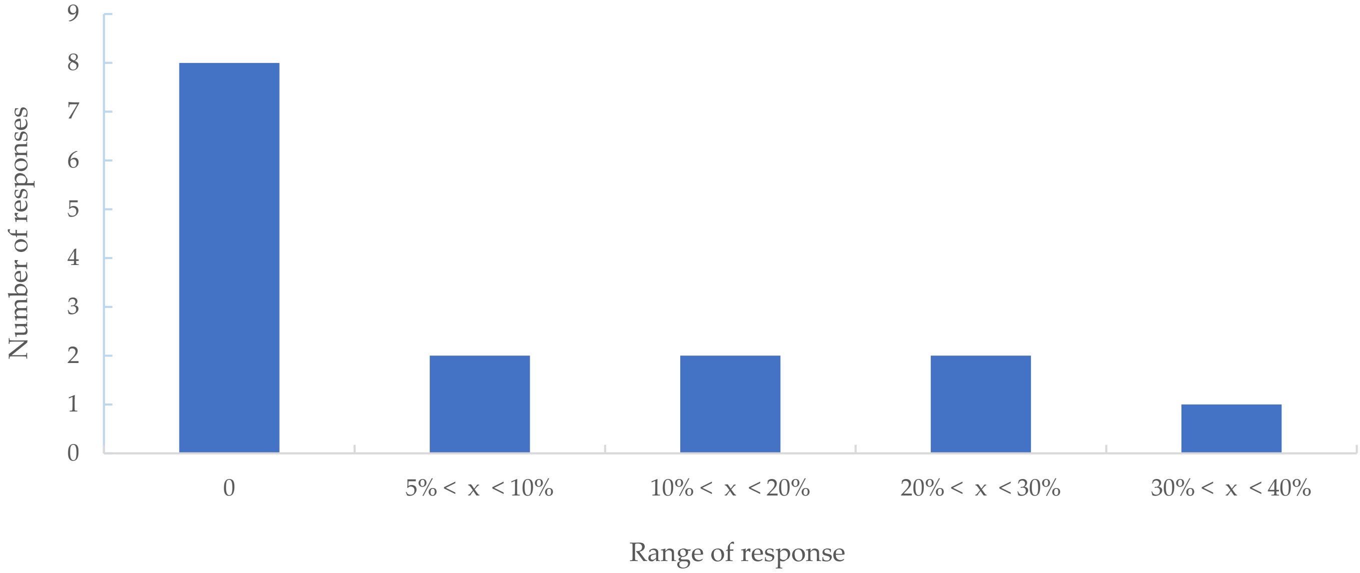

Figure 4. Increase in water demand due to the new crop rotations.

D. Triggering overall economic growth

We observe a strong agreement among experts that a transformation of the irrigation infrastructure would increase the country's GDP by 2030 (current contribution is 30%), with most respondents assuming increases within the range of 7% to 10% (Figure 5). All experts agreed that irrigated agriculture plays an important role in Uzbekistan's economy. They expect that modernization of irrigation systems by switching to drip or sprinkler irrigation may lead to a doubling of agricultural productivity in areas with water scarcity if the technologies are installed correctly. According to the Water Resources Development Strategy 2020–2030 (Presidential Decree No. 6024, adopted on 10 July 2020), water-saving irrigation technologies should be installed on 2 million ha (about 50% of the total irrigated area) of irrigated lands by 2030, out of which 600,000 ha should be installed with drip irrigation systems.

We summarize the expert-based assessment of rebound effects in the following two main statements. First, rebound effects are likely to occur due to increases in irrigation water use to compensate for existing irrigation water deficits and due to an increase in Uzbekistan's GDP. The majority of weighted responses assumed a current irrigation water deficit between 20% and 30%, and a GDP increase between 3% and 10%. Second, experts' assessments on whether farmers would increase their irrigated area or switch to more water-intensive crops or crop rotations differed strongly. Due to a lack of consensus among experts, our method was not able to make an assessment for these rebound categories. The highest number of weighted responses assumed a small expansion and no additional water demand from changed crop rotations, even though government policies, such as plans for agricultural expansion and programs for growing secondary crops, suggest otherwise.

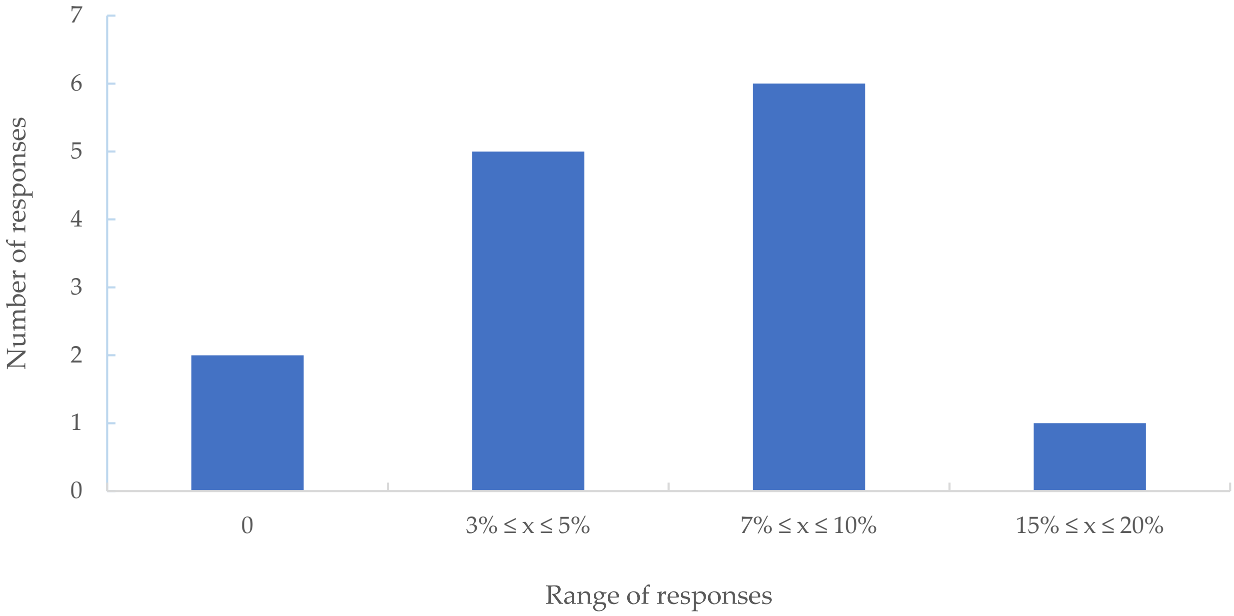

Figure 5. Estimated GDP increase as result of modernizing irrigation infrastructure.

4. Discussion

In this paper, we estimate potential economic rebound effects through expert-based assessment. To do so, we define the rebound effect as adaptive behavioral changes resulting from increases in resource use efficiency that partly or fully offset resource savings. In our analysis, we focus on economic mechanisms and quantify the effect as the share of resource savings that the water-saving technology application would achieve under *ceteris paribus* conditions (i.e., if water users would not change their behavior), but which does not materialize due to adaptations under real-life conditions in water and land use in Uzbekistan. As a result, our findings suggest that economic rebound effects are likely to occur in Uzbekistan in the near future:

- First, the study reveals a strong agreement among experts that the existing deficit concerning irrigation water is in the range of 20–30%. This estimation is in line with the results of other studies on water use in Uzbekistan [13,32]. For the Ferghana Valley of Central Asia, Milanova et al. [33] estimated the water deficit at 12%, increasing up to 38.2% by 2080. For Spain, Berbel et al. [30] found that rebound effects occurred where water deficits in the irrigation sector existed prior to the implementation of water-saving technology implementation.
- Second, interviewed respondents shared their knowledge about the current government plans for expanding irrigated lands by 2030 under internal discussion. However, with our method of individual interviews we were not able to elicit an agreement of this rebound mechanism or to clearly determine the reasons for disagreeing opinions. For disputed questions such as these, a workshop format with direct information sharing and options for discussion among the respondents would be more suitable and should be used in follow-up research. The potential of an increase in irrigated land after implementing water-saving technology is supported by recent trends in Uzbekistan. For instance, interviewed farmers in Bukhara province of Uzbekistan observe strong decline in groundwater table due to the increased irrigated lands combined with the installation of water-saving irrigation technologies. Furthermore, there are internal government discussions and multiple examples documented in other parts of the world [2,17].
- Third, most respondents assumed that the implementation of water-saving technologies is unlikely to increase water demand through changes in crop rotations, at least in the near future. However, the experts warned that policy changes of eradicating the

quota system for strategic crops and allowing farmers to cultivate secondary crops might trigger a switch to more water-intensive crops. Indeed, respondents interviewed in this study indicated that the policy change process has already been initiated, such as the government allowing or actively supporting the cultivation of secondary crops. Furthermore, a recent report by the Asian Development Bank (ADB) explains the trend of slowing agricultural production by observing increases in crop diversification and water deficits in Uzbekistan [34].

- Finally, the experts assess the economic impact of technology implementation at the national level to be significant, with GDP increases up to 10%. This is because of the important role of irrigated agriculture in Uzbekistan's national economy. For example, Djumaboev et al. [35] found that the introduction of drip irrigation technology in the Karshi steppe of Uzbekistan on 5 ha of land increased cotton yield by 13% compared to traditional furrow irrigation, and at the same time created water savings of over 50% (savings of 3590 m^3 per ha). An estimated increase of 10% in Uzbekistan's GDP is also in line with findings by Brody et al. [36]. However, the experts also noticed that the associated cost of technology implementation has to be considered (e.g., bank interest rates, technology installation, and maintenance costs). For instance, experts recommend localizing the technology by means of producing it in the country to make it more affordable for farmers. The economic impact of technology also depends on farmers' access to credit. This is particularly a challenge during the COVID-19 pandemic situation due to the increased interest rates and delays with bank credit approval. Last but not least, the technology's impact also depends on energy costs, as the average energy use of a pump to transfer water in drip-irrigated fields is approximately 400 kWh per day.

5. Conclusions

In this study, we argue that economic rebound effects are likely to occur in Uzbekistan in the near future due to: (1) the existing deficit in irrigation water; (2) expansion of irrigated lands; (3) switching to more water-intensive crops; and (4) increase in GDP.

The study results have significant policy implications as the Uzbek government expands its program of installing water-saving irrigation technologies over 2 million ha of irrigated lands (approximately 50% of total irrigated land) to increase irrigation efficiency from 0.63 to 0.73 (This estimation is presented in the Water Resources Development Strategy 2020–2030. However, the document does not clarify how these numbers were defined) (reducing the physical loss of water). This policy is outlined in the Water Resources Development Strategy 2020–2030, recently adopted by Uzbekistan's government. The policy objective to increase irrigation efficiency is expected to be achieved. During the Soviet era, furrow irrigation was used widely. In the 1980s, sprinkler and drip irrigation were tested and recommended as water-saving technologies. This experience was taken up again recently. It is expected that changing from furrow irrigation to sprinkler or drip irrigation would increase per hectare productivity, irrigation water productivity, the total production of agricultural commodities, and the GDP in Uzbekistan. However, due to rebound effects, the benefit of alleviating pressures on natural systems, such as on water availability in order to replenish water levels in the Aral Sea, is likely to be less pronounced than the higher technical irrigation efficiencies may suggest. Although our study indicates that there will be net resource savings even with rebound effects, additional policy measures beyond increases in irrigation efficiencies may be required to account for future water demand due to population increases, climate change, and economic growth. Therefore, our estimation of potential rebound effects provides a useful reference point for policy evaluation and adaptation. For example, policy adaptations may include controlling the expansion of irrigated areas, preventing the increase in overall water use, and ensuring a share of the achieved water savings is used for environmental goals (e.g., restoration of the Aral Sea).

This exploratory study focused on the economic mechanisms of the rebound effect at the national level. However, questions of provincial specificities and rebound effects at different scales (e.g., farming vs. water basin) were not incorporated. Moreover, in this study we applied an expert-based stakeholder assessment. In total, we conducted 18 interviews with stakeholders representing research organizations, state agencies, donor communities, private consulting firms, and resource users in winter and summer 2020. Due to the COVID-19 pandemic situation, access to Uzbek experts involved in this assessment was challenging. We are aware that the sampling size may not be representative of the whole country, but it provides important insights on how different stakeholders understand and assess the potential rebound effects in the future. Importantly, interviewed experts represent key organizations responsible for irrigation water management at the national, provincial, and local levels.

Thus, these shortcomings should be addressed in future studies. Additionally, there is great potential for expanding the assessment of rebound effects to other countries of Central Asia, as those nations are currently designing and implementing similar policies for adopting water-saving irrigation technologies. Finally, the linkages between the water, energy, and food sectors concerning the rebound effects require further investigation, especially in areas where electricity is used to lift irrigation water.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14148375/s1, S1. General information about the study area. S2. List of interviewed organizations. S3. Expert interview questions. References [37–46] are cited in the supplementary materials.

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