A framework for sustainable and inclusive irrigation development in Western Nepal

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Intensive cropping systems that include rice, wheat and/or maize are widespread throughout South Asia. These systems constitute the main economic activity in many rural areas and provide staple food for millions of people. Therefore, enhancing the yield and productivity of cereal production in South Asia is therefore of great concern. Simultaneously, issues of resource degradation, declining labor availability and climate variability pose steep challenges for achieving the goals of improving food security and rural livelihoods.

The Cereal Systems Initiative for South Asia (CSISA) was established in 2009 with a goal of benefitting more than eight million farmers by the end of 2023. The project is an exemplary sample of One CGIAR in action, and is led by the International Maize and Wheat Improvement Center (CIMMYT) and implemented jointly with the International Food Policy Research Institute (IFPRI), the International Water Mangement Institute (IWMI) and the International Rice Research Institute (IRRI). Operating in rural 'innovation hubs' in Bangladesh, India and Nepal, CSISA works to increase the adoption of various resource-conserving and climate-resilient technologies, and improve farmers' access to market information and enterprise development. CSISA supports women farmers by improving their access and exposure to modern and improved technological innovations, knowledge and entrepreneurial skills. CSISA works in synergy with regional and national efforts, collaborating with myriad public, civil society and private sector partners.

CSISA's Goals

- Facilitate the widespread adoption of resource-conserving practices, technologies and services that increase yields with lower water, labor and input costs.
- Support mainstreaming innovations in national-, state- and district-level government programs to improve long-term impacts achieved through investments in the agricultural sector.
- Generate and disseminate new knowledge on cropping system management practices that can withstand the impacts of climate change in South Asia.
- Improve the policy environment to facilitate the adoption of sustainable intensification technologies.
- Build strategic partnerships that can sustain and enhance the scale of benefits accrued through improving cereal system productivity.

With a new investment in the CSISA program, the USAID Mission in Nepal is supporting CSISA to rapidly and effectively respond to the threats posed by the Covid-19 crisis that undermine the recovery and sustained resilience of farmers in the FtF Zone of Nepal. This Activity includes Texas A&M University, Cornell University, and International Development Enterprises (iDE) as core partners. Activities involve two inter-linked Objectives that address CSISA's strengths in core areas needed to assist in Covid-19 response and recovery over an18 month period (From July 2020- December 2021). The ultimate goal of the CSISA Covid-19 Resilience Activity is to develop mechanisms to support longer-term resilience among smallholder farmers and the private sector – with emphasis empowering youth and overcoming challenges faced by women headed farm households. At the same time, the Activity is assisting in efforts to increase smallholder farmers' understanding of, and capacity to protect themselves, from Covid-19. This is achieved through the dissemination of awareness raising messages on public health and by increasing economic opportunities for return migrants, smallholder farmers, and by encouraging resilience-enhancing irrigation.

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List of Acronyms and Abbreviations

ADS	Agriculture Development Strategy
ca.	circa, or approximately
CGIAR	formerly the Consultative Group for International Agricultural Research
CIMMYT	International Maize and Wheat Improvement Center
COVID	Corona virus disease 2019
CSISA	Cereal Systems Initiative for South Asia
DoA	Department of Agriculture
FAO	Food and Agriculture Organization
FECOFUN	Federation of Community Forestry Users Nepal
FMIS	Farmer-Managed Irrigation System
FMIST	Farmer-Managed Irrigation System Promotion Trust
GCM	global circulation model
GESI	Gender Equality and Social Inclusion
GW	groundwater
GWRDB	Groundwater Resource Development Board
ha	hectare
HIMAWANTI	Himalayan Grassroots Women's Natural Resource Management Association
iDE	International Development Enterprises
INGO	international non-governmental organization
IWMI	International Water Management Institute
l	liter
MoALD	Ministry of Agriculture and Land Development
MoEWRI	Ministry of Energy, Water Resources and Irrigation
MSP	multi-stakeholder partnership
MUS	multiple-use water system
NARC	National Agriculture Research Center
NFIWUAN	National Association of Irrigation Water Users Association, Nepal
NGO	non-governmental organization
NLC	Nepal Law Commission
NNRFC	National Natural Resources and Fiscal Commission
NPC	National Planning Commission
NPR	Nepalese rupee
PMAMP	Prime Minister Agriculture Modernization Project
PPP	public-private partnership
RCM	regional climate model
RCP	representative concentration pathway
SNV	SNV Netherlands Development Organisation
SWAT	Soil and Water Assessment Tool
US	United States
USD	United States dollar
WASH	water, sanitation and hygiene
WECS	Water and Energy Commission Secretariat
WRP	Water Resources Policy
WUA	Water Users Association

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Executive Summary

Growing water risks threaten to severely derail Nepal's agricultural development ambitions, requiring substantial investments in better water resources management to meet food security targets, strengthen resilience, and encourage inclusive and private sector-driven growth in agriculture to support Nepal's transition to middle-income status by 2030.

Currently, irrigation development in Nepal focuses primarily on large-scale infrastructure, with insufficient data resources to support more adaptative and targeted coordination across sectors and stakeholders. As a result, irrigation development remains expensive and with limited reach relative to the country's needs, while missing opportunities to leverage the private sector, civil society, women and youth.

In response, building climate resilience and boosting agricultural productivity will require more adaptive and inclusive water management approaches. This report outlines three interlinked investment priorities informed by extensive country experience and more than one year of research. The three identified investment priorities are summarized as follows:

1. Ensure adaptive technology prioritization and water management practices which respond to local resource constraints and equity considerations.
2. Build robust data and information systems to allow adaptive planning, prepare for climate change impacts, and support digital agriculture and targeted farm advisories.
3. Expand and upgrade irrigation and agricultural value chains to ensure access to water, returns on investments, and the creation of better, more inclusive jobs.

Investments in these interlinked areas are expected to contribute to inclusive and sustainable irrigation development in Nepal which fosters resilient and equitable food system transformation. Subsequently, farmers may gain assured access to irrigation, with incentives in place to keep consumptive water use within an ecologically safe and socially just operating space. As a result, more resilient and higher agricultural production and farm incomes can be achieved, while safeguarding the rights of other water users and encouraging biodiversity conservation in neighboring ecosystems.

Sustainable and inclusive irrigation development

Policy and governance
Establish clear and inclusive multi-stakeholder coordination mechanism, institutional capacities, and evidence-based policies across levels of government, line ministries, and the private sector in line with constitutional principles.

Agricultural and irrigation value chains
Strengthen upstream and downstream industries and their linkages with strong GESI provisions and targeted demand-driven upgrading based on improved market intelligence and transdisciplinary understanding of key bottlenecks.

Water resources assessments
Strengthen data assests with open access policies, and institutionalize regular monitoring of water quantity and quality to build capacity for sustainable and adaptive management and conservation as water demand and climate change impacts increase.

Knowledge for agricultural water management
Leverage big data, digital transformation, and climate services to provide GESI-responsive, targeted, and bundled advisories and trainings on irrigation management, agronomic practices, and commercial aspects of farm management.

Infrastructure operation and management
Develop institutional capcity across all levels for GESI-responsive and sustainable management and development of smallholder and farmer-led irrigation infrastructure including groundwater and surface water systems.

Gender Equality and Social Inclusion
Integrate GESI provisions upfront across all sectors, programs, and policies to support sustained access and use of irrigation-led upgrading opportunities across value chains for climate-resilient and equitable food system transformation.

Gender Equality and Social Inclusion (GESI)

Climate Change

Capacity Building and Digitalisation

Local Empowerment

Above: key recommendations and cross-cutting issues for inclusive and sustainable irrigation development in Western Nepal.

1. Better water management for a food secure, resilient, and prosperous Nepal

1.1. Introduction

Growing water risks threaten to severely derail Nepal's agricultural development ambitions, requiring substantial investments in better water resources management to meet food security targets, strengthen resilience, and encourage inclusive and private sector-driven growth in agriculture to support Nepal's transition to middle-income status by 2030.

With the demand for healthy and nutritious food produced through climate-resilient agriculture on the rise, Nepal's agricultural sector is expected to meet these demands through poverty-reducing growth that increases the incomes of the many farmers and agriculturally employed. However, inadequate irrigation remains a major barrier to increasing agricultural productivity and boosting resilience to climate shocks, as irrigation access and use remain inequitable, insufficient and untimely.

This report assesses the current state of Nepal's irrigation sector and presents a sustainable and inclusive farmer-led irrigation development framework, that was co-created with key stakeholders to ensure that recommendations are in line with local development priorities. In brief, the report suggests that a re-orientation in the irrigation sector is needed towards more inclusive, service-oriented and farmer-led irrigation development. This would be achieved through more adaptive, evidence-based and demand-driven water management and technology investments, and would empower farmers, the private sector, and the newly established decentralized government structures defined in the 2015 Constitution.

We use the terms inclusive and sustainable farmer-led irrigation development to ensure that gender equality and social inclusion are front and center (inclusive), while environmental and cross-sectoral impacts are accounted for (sustainable), and that infrastructure development is demand-driven and strengthens the private sector (farmer-led). Importantly, the term development does not refer solely to infrastructure expansion, but to the development of improved policies and practices for the management of existing infrastructure and its surrounding economy, as well as targeted and demand-driven infrastructure expansion.

We have envisioned this document to support development planners and practitioners in guiding the formulation of irrigation investment programs. As such, this report is to provide an overview of the challenges and investment opportunities for sustainable and inclusive irrigation development in Nepal; it will serve as a guide for donors and policymakers working in the USAID Feed the Future (FtF) Zone of Influence but may also be adapted for use in other regions or countries. It draws upon key insights from the Cereal Systems Initiative for South Asia (CSISA) Activity: *Enabling effective COVID-19 crisis response in Nepal through appropriate agricultural machinery, resilience enhancing irrigation, and entrepreneurship.*

1.2. Structure of this report

The structure of the report mirrors the key elements required to catalyze farmer-led irrigation development – namely, governance, socio-economic, bio-physical and technological enablers – followed by additional information on how to apply the framework and a summary of key recommendations:

- Chapter 2 introduces the conceptual framework that has been developed for supporting sustainable and inclusive irrigation development in Nepal.
- Chapter 3 presents an overview of governance and socio-economic enablers in Nepal.
- Chapter 4 presents an overview of bio-physical and technological enablers in Nepal.
- Chapter 5 presents a case study of the Babai watershed to show how the framework together with scenario modeling can guide irrigation development in a specific watershed.
- Chapter 6 discusses the application of the framework to areas outside the USAID FtF Zone of Influence.
- Chapter 7 provides complementary information on sustainable groundwater management.
- Chapter 8 provides general recommendations drawn from the above chapters.

2. Introducing the framework

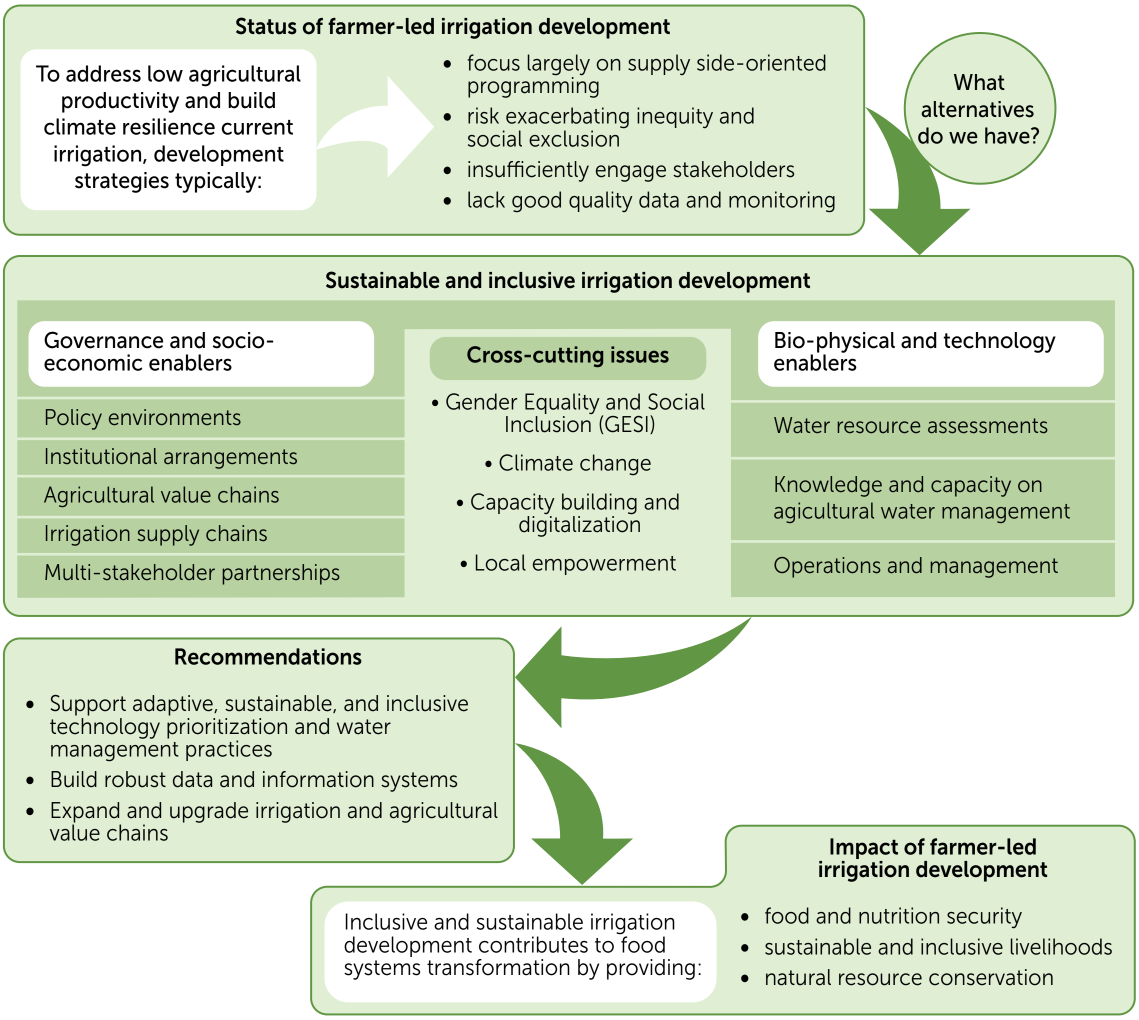
This section provides an overview of a Nepal-specific framework for inclusive and sustainable development of small-scale, farmer-led irrigation. The framework seeks to guide donors, decision-makers and implementing partners in co-designing targeted investments in sustainable and inclusive farmer-led irrigation development in the FtF Zone of Influence. Nepal's agri-food sector faces complex and intersecting challenges. Addressing these challenges requires accounting for governance, socio-economic, bio-physical, and technological enablers while considering the cross-cutting issues of gender equality and social inclusion, climate change, capacity building and digitalization, and local empowerment.

Importantly, inclusive irrigation requires continuous progress monitoring and adjustment of action plans based on lessons learned and emergent issues. This is true for Nepal's dynamic socio-economic and governance situation and the poorly understood (ground)water system. This framework thus provides a high-level snapshot based on analysis at the federal and subnational levels. Future programs can build on these insights and guide new program activities by localized applications (e.g. at watershed level) and iterative updates (e.g. annually).

The framework has been designed and validated through multi-stakeholder inputs together with USAID, the Government of Nepal, public and private sector partners, and farmers' representatives. It also benefitted from interactions at the field level with district and municipal decision-makers, irrigation scheme implementers and end users. The framework builds on key findings of CSISA-led irrigation assessments including:

1. systemic analysis of barriers, socio-economic and institutional challenges (Khadka, Uprety, Shrestha, Minh et al., 2021)
2. assessment of opportunities for conjunctive water use (V. P. Pandey et al., 2021)
3. integrated hydrologic modeling and machine-learning analysis of irrigation development scenarios (Risal et al., submitted for publication; McDonald et al., in preparation)
4. piloting of digital groundwater monitoring (Urfels et al., in preparation).

These reports have been further supplemented by an extensive review of published scientific literature, national policies and strategy documents concerning irrigation management. Collectively, these help to define the enabling conditions and investment priorities to ensure effective, gender and socially inclusive farmer-led irrigation, underpinned by sustainable natural resource management (Figure 1).



Status of farmer-led irrigation development

To address low agricultural productivity and build climate resilience current irrigation, development strategies typically:

- focus largely on supply side-oriented programming
- risk exacerbating inequity and social exclusion
- insufficiently engage stakeholders
- lack good quality data and monitoring

What alternatives do we have?

Sustainable and inclusive irrigation development

Governance and socio-economic enablers

- Policy environments
- Institutional arrangements
- Agricultural value chains
- Irrigation supply chains
- Multi-stakeholder partnerships

Cross-cutting issues

- Gender Equality and Social Inclusion (GESI)
- Climate change
- Capacity building and digitalization
- Local empowerment

Bio-physical and technology enablers

- Water resource assessments
- Knowledge and capacity on agicultural water management
- Operations and management

Recommendations

- Support adaptive, sustainable, and inclusive technology prioritization and water management practices
- Build robust data and information systems
- Expand and upgrade irrigation and agricultural value chains

Inclusive and sustainable irrigation development contributes to food systems transformation by providing:

Impact of farmer-led irrigation development

- food and nutrition security
- sustainable and inclusive livelihoods
- natural resource conservation

Figure 1. Conceptual diagram of the structure underpinning the Sustainable and Inclusive Irrigation Framework for Western Nepal.

3. Governance and socio-economic enablers

3.1. Policy environments

The Government of Nepal is developing several policy frameworks to steer line ministries in aligning constitutional provisions with the federal governance system. Overall, the Nepal Constitution 2015 sets out adequate guiding principles and provisions for inclusive and sustainable irrigation development, but these are increasingly poorly integrated down from federal policies to local policies and implementation. This section provides an overview of the constitutional provisions and key sectoral policies.

3.1.1. Constitutional provisions for water resources and irrigation development

The Constitution of Nepal 2015 provides a solid foundation for water and natural resources management and includes strategic considerations on tackling poverty, food insecurity, inequality and environmental degradation. The constitutional provisions require women and historically marginalized groups to participate in and benefit from farmer-led irrigation development (Khadka, Uprety, Shrestha, Minh, et al., 2021), and significantly recognizes the roles of water resources, irrigation, renewable energy and agriculture development for the socio-economic development of the country.

Article 51 sub-clause (g) sets out the State's policy on the conservation, management and use of natural resources, with three of the nine provisions to be directly linked to water resources and irrigation development. The provisions in Article 51 sub-clause (g) focus on the State's roles to:

1. ensure the fair distribution of benefits generated by sustainable natural resource management by giving local people the priority and preferential rights
2. pursue a policy of prioritizing national investment in the multi-purpose development of water resources based on people's participation
3. develop a reliable and sustainable irrigation system by preventing water-induced disasters and river management.

Article 51 sub-clause (e) envisions the commercialization, industrialization, diversification and modernization of agriculture, while protecting the rights and interests of farmers and ensuring their access to extension services, and appropriate markets and prices.

Article 50 sets out the Directive Principles that ensure the State's accountability for gender equality, proportionate inclusion, participation and social justice. Further principles that promote gender equality, proportionate inclusion, participation, social justice, the fundamental right to safe drinking water and clean environment and equitable society are detailed in Articles 18, 35, 38, 40, 42, 50 and 51.

3.1.2. Water, land and agriculture and trade policies

Overall, national policies recognize the importance of irrigation for increasing agricultural productivity and spurring economic growth, but most poorly reflect provisions for gender equality, social inclusion, farmer-led irrigation development and water quality, while favoring large-scale water infrastructure development, mechanization and commercialization of agriculture (Khadka, Uprety, Shrestha, Minh, et al., 2021).

Agricultural water management policies. The National Irrigation Master Plan 2019 is the government's major irrigation policy document and details a 25-year vision to support the development targets set out in the Agriculture Development Strategy (ADS) by increasing year-round irrigation coverage from the current 18% of irrigable land to 80% (Tractebel Engineering GmbH, 2019). GESI is limited to 33% reservation in water user associations (WUAs) (Khadka, Uprety, Shrestha, Minh, et al., 2021). Groundwater also receives little attention, although it is the main source of irrigation for over 50% of the farmers. Better groundwater irrigation management can significantly improve equitable water access and use. For example, high costs of irrigation pumps and well-drilling services by smallholder farmers can be reduced through better pump selection and drilling methods (Foster et al., 2021; Foster & Urfels, 2020a) and a collective approach can facilitate improved water access and use by women, marginal and tenant farmers (Foster et al., 2019; Sugden et al., 2020).

Water resources policies. Key water resources policies focus on large-scale water infrastructure, management and water quality for socio-economic prosperity in the country, and recognize access to water as the citizens' right; however, they do not include GESI-specific measures to ensure representation of rights-holders, civil society organizations, women and marginalized groups in water governance and community management. Key policies include the National Water Resources Policy 2020, Draft Water Resources Act (2020) and Drinking Water and Sanitation Bill 2019 (MoEWRI, 2020). GESI sensitization, policy advocacies and vertical and horizontal integration of policies provide key entry points for ensuring that infrastructure development is demand-driven and inclusive (Khadka, Uprety, Shrestha, Minh et al., 2021).

Agriculture policies. In contrast to water resources policies, agriculture policies promise to implement GESI-sensitive, water–food–energy nexus programs targeted at smallholders and youth, but neglect building resilience against the projected impact of climatic change (Khadka, Uprety, Shrestha, Minh et al., 2021). The Ministry of Agriculture and Livestock has produced 25 policies over the last three years (Acharya, 2021), but climate impact on agricultural production and irrigation access receive little attention. The ADS (2015–2035) was prepared prior to federalism and is being revised; it aims to achieve food and nutrition security targeting food self-sufficiency for Nepal with a 5% trade surplus by 2033 (Khadka, Uprety, Shrestha, Mukherji et al., 2021).

Youth policies. The National Youth Policy 2015 and Youth Vision 2025 ensure the Government of Nepal's commitment to empowering youth in agriculture development and the national economy. However, their implementation is constrained by a lack of cross-sectoral coordination, and duplication of youth programs among 18 ministries (J. Pandey, 2018). Irrigation programs may therefore aim to facilitate cross-sectoral linkages and coordinated programming for better engagement of youth in and socio-economic outcomes of irrigation development.

Trade policies. Trade and macroeconomic policies pursue an export promotion strategy to increase income and build value chains including agricultural products and women-led enterprises. For example, the Trade Policy 2015 and Nepal Trade Integration Strategy 2016 aim to promote exports and strengthen export value chains such as agro-forestry products, with emphasis on e-commerce, tax refunds on raw materials, small and medium enterprises, and enterprises led or owned by women and marginalized groups. Product focus includes cardamom, ginger, tea and medicinal and aromatic plants, and aims to expand these to new areas such as private sector actor investment and public-private partnerships (PPP). Of note is that since 2019 Nepal and China are implementing the Transit and Transportation Agreement to allow Nepal the use of four Chinese sea ports and three land ports, facilitating imports of machinery to Nepal (Giri, 2019).

Tax policies. The Financial Act 2019, Draft Financial Bill (2020) and Industrial Enterprise Act 2018 provide subsidies for irrigation and agriculture equipment for private sector actors including zero VAT or tax for importing agricultural products and tools, including solar equipment. Women are also explicitly supported with, for example, a 25% tax exemption when registering land in a woman's name, a 30% discount on enterprise registration fees, and a 15% income tax waiver for firms employing at least 50% women and members of other marginalized groups (Khadka, Uprety, Shrestha, Minh et al., 2021).

Public and private sector partnership policies. The government increasingly engages with national and international private sector actors for national development as outlined, for instance, in the PPP and Investment Act 2018 and PPP Rule 2019. Over seven national policies and items of legislation promote PPP-based trade and agro-enterprises to increase economic opportunity, jobs and employment. However, there is scope for private sector policies to be more irrigation-focussed, pro-poor, and inclusive of marginalized groups and women (Khadka, Uprety, Shrestha, Minh et al., 2021). The policies focus on infrastructure investments in the forms of loans, equity or refinance, or the transfer of technology. These policies may be improved by, for example, including GESI provisions for committees and expert groups and a more explicit focus on the irrigation sector (Khadka, Uprety, Shrestha, Minh et al., 2021).

Subsidy policies. Agricultural subsidy policies by federal and provincial governments aim to boost agricultural development and provide limited subsidies for irrigation, women and marginalized groups. A total of 116,096 documented irrigation wells and pumps have been subsidized in the FtF Zone of Influence districts. The subsidies mainly target rain-fed agriculture, and prioritize seed and fertilizer instead of irrigation equipment for which the government is spending NPR 18 billion (ca. USD154 million) annually (Khadka, Uprety, Shrestha, Minh et al., 2021). Subsidies often do not reach poor, women or marginalized farmers due to the limited monitoring of the implementation of subsidy programs, and inadequate review and design of subsidy policies and programs (Khanal et al., 2020b). Irrigation subsidies face similar challenges such as for solar-powered irrigation pumps. For example, to access the 60% subsidy a farmer household has to submit a copy of their land ownership certificate and citizenship and a recommendation letter from their local government, and have a minimum land size of 1 ha (Khanal et al., 2020a) which many small, women and marginal farmers do not own (Khadka, Uprety, Shrestha, Minh et al., 2021).

3.2. Governance and institutional arrangements for irrigation development

The 2015 Constitution has introduced a three-level federal structure with a total of 761 governmental units: 1 federal, 7 provincial and 753 local governmental units (Khadka et al. 2021). Substantial capacity-building efforts and dedicated local resources will be required for the new decentralized governmental units to successfully implement their mandates on sustainable and inclusive irrigation development, and cross-sectoral and cross-scale coordination.

3.2.1. Jurisdiction and cooperation among three levels of government

All three levels of government have the constitutional power to enact laws, prepare budgets and mobilize their own resources (S. Shrestha et al., 2019). The 2015 Constitution defines the jurisdictions of federal, provincial and local level governments regarding water resources, irrigation and water supply (Table 1). There has been a historic shift in irrigation policymaking and development towards the local level since the institutionalization of federalism. The Local Government Operation Act 2017 defines the exclusive power of local governments and is an influential policy framework for sustainable and inclusive irrigation and agriculture development (Thapa et al., 2019). Local governments are directly responsible for managing the competing use of limited water and land resources, managing natural resources conflicts, and coordinating with stakeholders (Tractebel Engineering GmbH, 2019) (CAMRIS, 2020; DRCN, 2020) (Khadka, Uprety, Shrestha, Minh et al., 2021). This presents an opportunity to scale farmer-led irrigation technologies with the technical and financial support of non-governmental organizations, research institutes, the private sector, investors and finance institutions. While the federal laws are in the process of being drafted, the government's Business Rule 2019 defines which level of government has jurisdiction over irrigation projects according to their size, as follows:

- The federal government manages irrigation projects with command areas of more than 5000 ha in the Tarai, 300 ha in the hilly areas and 100 ha in mountain areas.
- The provincial government is responsible for irrigation projects between 200 to 5000 ha in the Tarai, 50 to 100 ha in hilly areas and 25 to 50 ha in mountain areas.
- Local government is responsible for all irrigation projects and systems covering areas less than that which the provinces are responsible for.

However, insufficient technical and financial capacity at local and provincial levels, and unclarity on mandates between level of government limit the implementation of smaller-scale irrigation support programs, resulting largely in capital subsidies for irrigation pump and tubewells – and sidelining crucial knowledge management, behavioral change on water use and production, and equity issues (Khadka, Uprety, Shrestha, Minh et al., 2021). Improving the technical and management capacities of local government and improving coordination present great opportunities for sustainable and inclusive irrigation development.

Table 1. Jurisdiction of three levels of government for water resources, irrigation, and related sectors, indicating overlapping responsibilities and exclusive rights.

Provision of rights	Single and common rights of the government		
	Federal	Provincial	Local
International treaties and agreements and transboundary rivers	✓		
Conservation and multiple uses of water resources	✓		
Central-level large projects on electricity, irrigation and other projects	✓		
National and global environmental management and wetlands	✓		
Provincial electricity, irrigation and water supply services		✓	
Land management and land documentation		✓	
Provincial water resources use and environmental management		✓	
Agriculture and livestock development		✓	
Local-level development projects and programs			✓
Basic health and sanitation			✓
Local market management, environment conservation and biodiversity			✓
Agricultural extension services			✓
Water supply, small hydropower and alternative energy			✓
Disaster risk management			✓
Local roads, rural roads, agro-roads, irrigation			✓
Watershed conservation			✓
Provincial boundary rivers, waterways, environmental protection and biodiversity	✓	✓	
Disaster risk management	✓	✓	
Water supply and sanitation	✓	✓	
Inter-province water uses	✓	✓	
Services such as energy, water supply, irrigation	✓	✓	✓
Service fees, charges, penalties and royalties from natural resources	✓	✓	✓
Water use, environment, ecology and biodiversity	✓	✓	✓
Disaster risk management	✓	✓	✓

Source: Adapted from the Constitution of Nepal 2015, Unbundling Report 2016, Government of Nepal.

Note: Exclusive or single rights of federal, provincial and local governments are defined by schedule 5, 6 and 8 of the 2015 Constitution. Common rights between the provincial and federal level are included in schedule 7, and common rights among the three levels of government are included in schedule 9.

3.2.2. Public sector institutional arrangements for water resources and irrigation development

The federal system demands cross-sectoral collaboration and coordination on water governance and management. However, limited clarity on roles among public water institutions and overlapping responsibilities pose barriers to the effective coordination required to provide reliable water services (Sharma & Adhikary, 2020), raising a need for restructuring water institutions in alignment with the Constitution (FMIST, 2020; Suhardiman et al., 2018).

At the federal level, the Ministry of Energy, Water Resources, and Irrigation (MoEWRI) is the key line ministry for developing national water policy and legislation with the three departments: Department of Water Resources and Irrigation, the Department of Electricity Development and the Department of Hydrology and Meteorology. Additional entities within MoEWRI such as boards and centers provide further policy and technical expertise on water resources, groundwater and energy.

After MoEWRI, another 10 ministries have a role pertaining to water resources, watershed management, irrigation and conservation (Khadka et al. 2021b). The Water and Energy Commission Secretariat (WECS) develops policies on river basin management, planning and coordination but does not retain national direction-setting roles under federalism (FMIST, 2020). Strengthening sustainable water management capacities alongside infrastructure investments remains a key opportunity across WECS and other institutions (FMIST, 2020; Suhardiman et al., 2018).

Finally, two constitutional bodies have the mandate to define resource distribution and coordination mechanisms: the well-established National Planning Commission (NPC) and the newly established National Natural Resources and Fiscal Commission (NNRFC). The NPC defines frameworks for national policies and planning while the NNRFC guides the distribution of revenues from natural resources across the levels of government as, for example, outlined in the Inter-Governmental Fiscal Management Act, 2017, which requires revenues to be distributed as 50% (federal), 25% (provincial) and 25% (local) (NLC, 2017). However, continued contestation about resource and budget distribution is expected, especially between upstream and downstream actors (Khadka, Uprety, Shrestha, Minh et al., 2021; D. P. Poudel & Khatri, 2019).

3.3. Agricultural value chain

Inclusive and sustainable irrigation development requires well-functioning agricultural value chains for the timely and affordable provision of high quality inputs, fairly priced output markets, and appropriate post-harvest facilities (Figure 2). In Nepal, there is scope to strengthen these elements through inclusive and coordinated investments in upgrading downstream and upstream value chains to catalyze irrigation-supported productivity improvements. This is especially true for high value crops such as fruits, nuts and vegetables, as well as for field crops in more remote areas.

Major cereals such as rice and maize are the country's main staples, while vegetables are high value commodities grown on a limited amount of land. The hills have poorer grain markets than the Tarai (Gurung et al., 2011), and so District Seed Self-Sufficiency Program groups and community-based seed production groups help with seed access (Gurung et al., 2011) while several government offices, NGOs, cooperatives and microfinance organizations support value actors in coordinating the upgrading of their operations and facilities (Honsberger, 2015; Yadaw, 2018).

3.3.1. Major issues and barriers

Major issues in Nepal's agricultural value chains pertain to poor fertilizer supplies and road networks, irresponsive markets, high post-harvest losses, high irrigation prices, inadequate access to finance, and discrimination against marginalized social groups including women. For example, untimely and insufficient fertilizer supply is only being slowly amended by the development of more dynamic private sector with relatively large quantities of fertilizer (previously 70%) still being illegally imported from India (Panta, 2018; Saini, 2020)(Prasain & Giri, 2015)(MOAD, 2016). Similarly, large markets such as the Kalimati wholesale market in Kathmandu are dominated by small groups leading to less

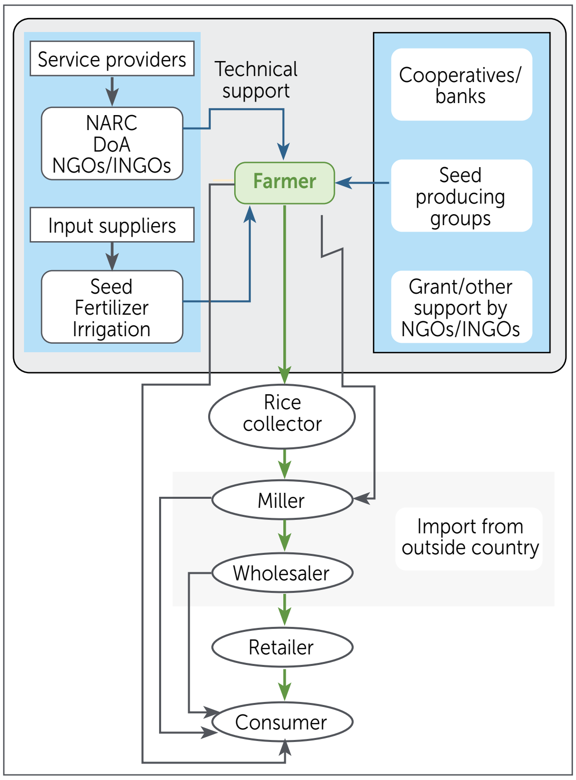


Figure 2. Cereal supply chain in Nepal (adapted from Yadaw, 2018).

bargaining power for farmers (Khadka, Uprety, Shrestha, Minh et al., 2021). Furthermore, only 21.5% of farmers with less than two hectares of land have access to finance compared to 39% of farmers with more than two hectares (CBS, 2013), and thus rely on informal lending (CBS, 2013). Most importantly however, few women participate in value chains. Weakening their position when negotiating prices or applying for training (Honsberger, 2015).

3.3.2. Key opportunities and enablers

Several important windows of opportunity exist across agricultural value chains starting with five commodity value chains, identified by the ADS – maize, dairy, lentil, tea and vegetables – for poverty reduction and economic growth. Each value chain is supported by a Value Chain Program Steering Committee consisting of farmers, agri-business enterprises and extension service representatives (Khanal et al., 2020b). These programs also provide opportunities for on- and off-farm livelihood improvements of women, marginalized groups and smallholders. Importantly, the ADS seeks to bolster the role of the private sector, for example for fertilizer supply, and to actively enable resource-poor farmers to better connect to markets by mobilizing the private sector, the government, and development partners. Lastly, microfinance and agricultural cooperatives provide crucial opportunities for lending and saving services to penetrate rural spaces. For example, the Small Farmer Development Microfinance Financial Institution Limited provides credit requiring only relatively little or no collateral. Cooperatives help smallholders negotiate their positions in bigger markets and have contributed to significantly improving women's financial access and further positively impacting household decision-making (G. Poudel & Pokharel, 2018). Importantly, supporting small and medium enterprises contributes substantially to off-farm incomes with 275,433 registered SMEs in Nepal, as of 2017/18 (Bista, 2019) providing 1.7 million jobs (Khadka, Uprety, Shrestha, Minh et al., 2021) and increasingly for women (farmers) (UN Women, 2017).

3.3.3. GESI-related challenges and opportunities

More GESI-responsive investments in value chains could help create better opportunities for women and marginalized groups, but participation is constrained by a systemic under-representation in public and private sector institutions dealing with agricultural services (FAO, 2019). Few professionals who are women or from marginalized groups translates into the limited reach of GESI-responsive information and services. For example, local gender and social norms prevent women's mobility and interactions with men – especially outside kinship circles (Subedi, 2018), so that a lack of female dealers, extension agents, and technicians encumbers access to input, markets, and information (Joshi, 2018). Nevertheless, women lead 30% of firms in Nepal (UNDP, 2020) but only 11% of staff in public agricultural services (FAO, 2019). Strengthening women's agency and leadership, and the active promotion of women-owned businesses, female technicians, engineers and agriculture extension workers can capitalize on the large male out-migration that, despite the recent COVID-19-related dampening, is creating increasing opportunities for women (Gartaula et al., 2010; Maharjan et al., 2012; Ministry of Labor, Employment and Social Security, 2020). Women-focused programs need especially to address the country's low literacy levels, social norms and time restrictions (Stoian et al., 2018).

3.4. Irrigation value chain

Since the 1980s and especially the early 2000s, private sector actors have been instrumental in bringing new technologies, skills and ideas into the irrigation sector in Nepal – providing farmers with access to climate-resilient irrigation technologies. Building on these private sector networks will be crucial in setting water use incentives, improving knowledge of good irrigation practices, and catalyzing markets for produce and services (Lefore et al., 2019; Minh et al., 2021). High irrigation costs are the major barrier for better irrigation, as most farmers have to rent expensive groundwater diesel pumps for irrigation (Foster & Urfels, 2020a). However, most pump owners irrigate late due to high diesel costs, while pump renters have to also queue for equipment (pumps, shallow tubewells) and convince pump owners to accept delayed payments in the absence of sufficient cash and credit (Urfels et al., 2020c). Improving the irrigation supply chain and developing technologies to improve access and use is therefore crucial for sustainable and inclusive irrigation development. Figure 3 shows the mapping of the irrigation supply chain for Nepal.

3.4.1. Irrigation equipment

Farmers use different irrigation equipment depending on the crops grown, farm size, and investment capacities. Almost all pumps (solar, electric, diesel, petrol) and their components are imported from India and China. Indian pumps are most popular but Chinese pumps, due to their low cost, are increasingly gaining market share, while Italian firm Pedrollo is popular for solar pumps (Khadka et al., 2021). Domestic irrigation equipment manufacturing focuses largely on plastic-based components including drip kits, sprinklers, tubewell fittings, lay-flat pipes and greenhouse plastics, relying on imported high quality polymers and plastics (Khadka et al., 2021). Irrigation vendors are therefore dependent mostly on import–export companies and authorized distributors in the supply chain, as these importers maintain standard stock supply and handle importation and related duties. Vendors then deploy irrigation equipment by using regional distribution and sales offices

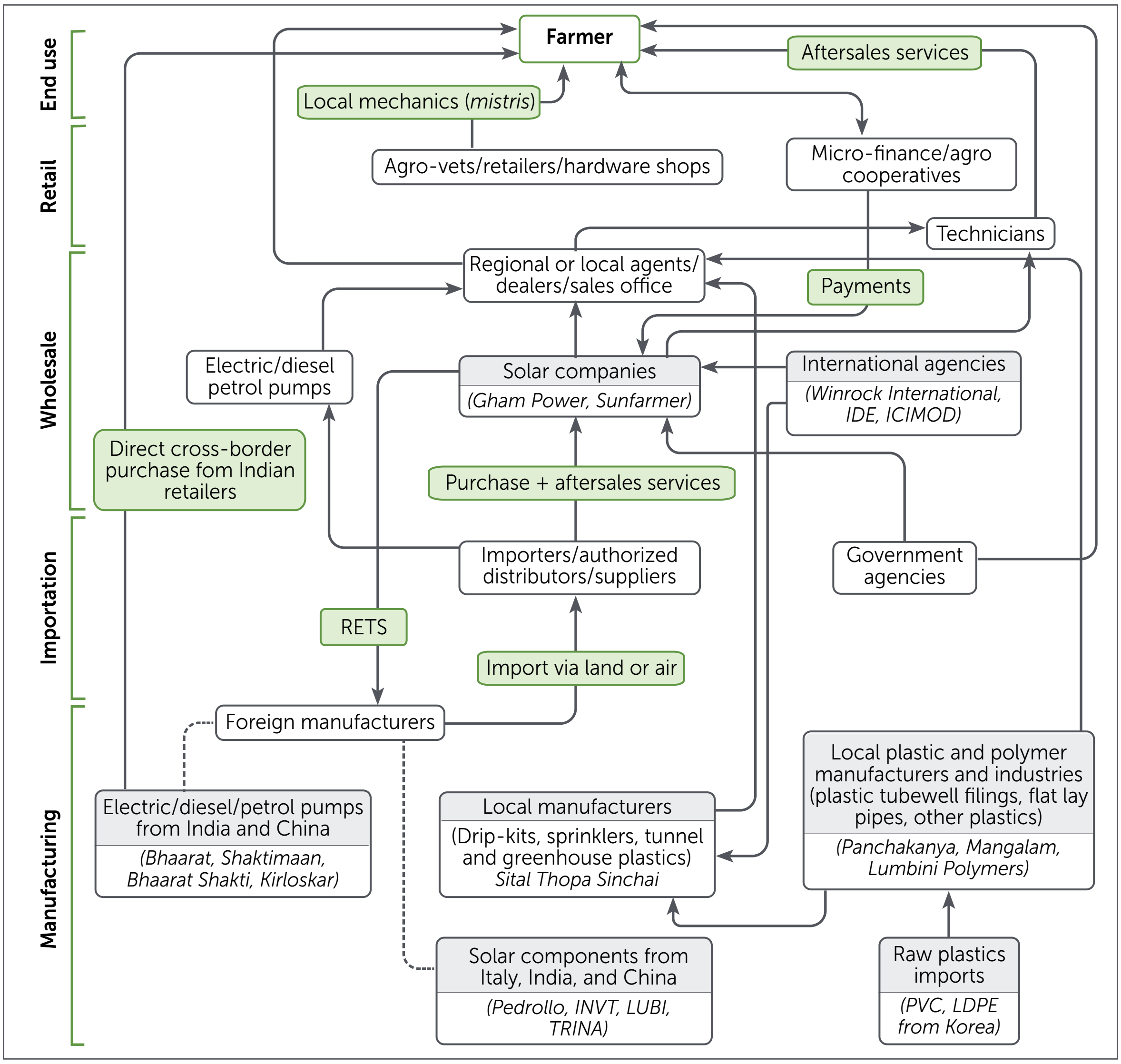


Figure 3. Private irrigation equipment supply chain, Nepal. Primary data and analysis by Uprety (2020) in (Khadka et al., 2021, p. 33).

and/or regional agents across the country, from where smaller retail shops procure equipment and the farmer buys it. Direct cross-border equipment purchases from India including more affordable second-hand pumps are also common in the Tarai. Local mechanics and technicians commonly called *mistris* are engaged by farmers in well-drilling services – *mistris* are often connected to hardware shops (Yoder & Adhikari, 2015) and also offer repair services for electric/diesel/petrol pumps (Yoder & Adhikari, 2015).

3.4.2. Barriers and opportunities

The irrigation equipment supply chain faces several barriers in Nepal. These include tariffs and costly trade routes, insufficient availability of spares and repairs networks, ineffective access modalities, and energy constraints. Conducive trade and manufacturing environments are crucial for irrigation supply chains (Khadka, Uprety, Shrestha, Minh et al., 2021), but variably applied tariffs and taxes (Khadka, Uprety, Shrestha, Minh et al., 2021), unreliable land ports with frequent closures, and poor transport conditions (especially in the hills) increase trading costs and the risks of doing business (Khadka, Uprety, Shrestha, Minh et al., 2021). With sufficient support to the private sector, the recent permission granted to Nepal by China to make use of its seaports (in Tianjin, Shenzhen, Lianyungang and Zhanjiang) and land ports (in Lanzhou, Lhasa and Shigatse) (Giri, 2019) may help to overcome some of these obstacles. In addition, improving the local manufacturing market including spares and repairs networks is crucial for enabling inclusive farmer-led irrigation development. Nepal's domestic pump market has a large potential to expand, with pump imports increasing from NPR950 million to NPR4 billion (approx. USD8.1 million to USD33.9 million) over the last decade (Pokharel et al., 2020). However, for most irrigation pumps, spare parts are not readily available in Nepal, with queues tending to form at repair shops during times of great irrigation need. Opportunities exist, with the new budget of

2021/22 stipulating tax waivers on the import of raw agro-products and tax subsidies on importing agro-equipment, in addition to 50% subsidies for local organic fertilizer production (myRepublica, 2021). Upfront capital costs also limit the ability of small farmers to invest in irrigation. Public-private partnerships for farm equipment-leasing, as envisioned in the Prime Minister Agriculture Modernization Project (PMAMP) and the Agriculture Mechanization Promotion Policy 2014, could support farmers by reducing costs and access barriers, and building capacity in good agricultural and water management practices (Urfels et al., 2020a).

Three major energy options for powering farmer-led irrigation exist in Nepal – diesel, electric grid and solar – each with its own limits and opportunities. Around 80% of shallow tubewells are powered by diesel pumps (Nepal et al., 2019), the remainder being largely powered by the electric grid and a small but burgeoning number of solar irrigation systems. Diesel pumps are ubiquitous, with relatively easy access and different models providing private sector-driven, affordable, mobile, high capacity and on-demand irrigation, with significant opportunities to further reduce prices and increase efficiencies through better pump selection. These however remain subject to fuel price fluctuations and shortages (Foster & Urfels, 2020b; Havana, 2015; Urfels et al., 2020a). Electric pumps are significantly more efficient and climate-friendly when powered by renewable energy, but with only 3.3% of energy potential explored, the small and unreliable national electric grid often creates more problems and delays than it solves. Solar irrigation promises to tackle some of these issues but often lacks the required repair and maintenance services and has significantly higher capital costs that amount to ~USD2000 for solar pumps compared to ~USD150–350 for diesel and electric pumps. Financial schemes exist to overcome solar power's high capital costs and include grants, rent-to-own models and grant-cum-loan models (S. Shrestha & Uprety, 2021). With these support programs, the number of solar irrigation pumps has increased sharply from 75 in 2016/17 (supported by the Alternative Energy Promotion Centre) to 1056 in 2018/19 (Pandey et al., 2020). Inclusive and sustainable irrigation development will require careful and context-sensitive targeting of the different technologies for different needs, based on capital and operating costs, crop water demand, water lifting capacity, mobility to irrigate plots away from the homestead, energy availability, strength of the spares and repairs network, and expected rates of return depending on the irrigated crops and soil types.

3.4.3. GESI in the irrigation supply chain

Women and marginalized groups lack access to or ownership of irrigation equipment, subsidies and credit, even though they constitute the majority of the agricultural workforce (Bastakoti et al., 2017; Sugden, 2014). For example, technology ownership and operation are generally considered men's responsibility, making it hard for women to break such gender norms. In addition, short-term tenancy contracts discourage tenant farmers from investing in groundwater wells and they are unable to access subsidies. Similarly, smaller farming households, tenant farmers and women farmers tend to rely on costly rental rates for shared diesel pumps and on informal contracts with landowners (Sugden, 2014; Sugden et al., 2020). Promoting tenant farmer collectives could enhance their bargaining and negotiating power with regard to accessing agriculture and irrigation services (Sugden et al., 2020), while creating a channel by which the private sector can present their offers to these groups. Some private sector actors already consider GESI in their activities – for example, by setting targets for women technicians – but mainstreaming GESI more broadly is imperative, through targeted advisory services, custom-hiring centers and affirmative subsidies for women farmers (Khadka, Uprety, Shrestha, Minh et al., 2021).

3.5. Multi-stakeholder partnerships for irrigation development

3.5.1. Building an ecosystem to accelerate irrigation development

Sustainable and inclusive irrigation development in Nepal requires integrated cross-sectional efforts that strengthen the capacity of the newly empowered local governments. Multi-stakeholder partnerships can facilitate technology adoption (Brown et al., 2021) but the irrigation sector lacks a multi-stakeholder platform that connects diverse actors such as the public and private sector, NGOs, CSOs, farmers, research, and community institutions (Khadka, Uprety, Shrestha, Minh et al., 2021). Therefore, future irrigation development should consider designing, piloting, and scaling multi-stakeholder platforms as a governance mechanism of sustainable irrigation development.

The following sections provide an overview of actors that should be considered when developing multi-stakeholder partnerships.

3.5.2. Government agencies

At the federal level, MoEWRI and its departments are the key actors (section 3.2). There there are several additional entities under MoEWRI: the Alternative Energy Promotion Center is a nodal agency for promoting renewable energy technology including solar-powered irrigation pumps, and the Groundwater Resource Development Board (GWRDB) has the mandate for investigating aquifers, delineating groundwater potential areas in the Tarai, as well as monitoring, assessing risk and regulating the use of groundwater. The Water Resources Research and Development Center and the National Agriculture Research Center are involved in research and capacity building on water resources, quality, availability and uses, and agriculture and horticulture crops (Khadka, Uprety, Shrestha, Minh et al., 2021).

At the provincial level, the Ministry of Physical Infrastructure Development and its division offices have roles regarding irrigation development as described in section 3.2. The Agriculture Knowledge Center, Soil and Watershed Management Offices and Forest Divisions are the main actors that coordinate and implement agriculture, soil and watershed conservation, agro-forestry and climate adaptation and mitigation programs. The Directorate of Industry, Commerce and Consumer Protection along with domestic and small enterprise offices coordinates and provides services relating to technical capacity building, public and private sector investment, and enterprise registration (Khadka, Uprety, Shrestha, Minh et al., 2021).

At the local level, local governments are the main players for development, including irrigation, watershed conservation and agricultural development. Their Agriculture Services Centers and irrigation staff interface with the provincial line agencies and services providers to obtain inputs and services for farmers (Khadka, Uprety, Shrestha, Minh et al., 2021). As these local governments are new entities, they operate with limited capacity and knowledge of water management, gender and social inclusion (Khadka et al., 2021). Irrigation development programs should partner strongly with local governments as the lead local government agency.

3.5.3. Private sector actors

As described in sections 3.3. and 3.4, leveraging Nepal's dynamic private sector is critical for sustainable and inclusive irrigation development. Creating an institutional environment that values the private sector requires viewing private sector actors not as 'contractors' but as 'leaders' of irrigation and agricultural technology and services innovation with business models that strengthen irrigated agriculture value chains and sustainable irrigation services (Khadka, Uprety, Shrestha, Minh et al., 2021).

3.5.4. Community-based institutions as key scaling stakeholders

Over 91,000 grassroots water and natural resources management institutions offer networks for scaling irrigation technologies and practices and include water user groups, forestry user groups, farmer groups (Khadka, Uprety, Shrestha, Minh et al., 2021). In particular, the federation of irrigation user groups (NFIWUAN), community forest user groups (FECOFUN), women's natural resources management groups (e.g. HIMAWANTI] and association of Small Farmers Cooperative Limited are key civil society organizations for raising people's voices on scaling challenges and solutions at the policy level, and their networks exist from local to provincial and federal levels.

3.5.5. National and international non-governmental organization

With capacity gaps in delivering public services, the Government of Nepal acknowledges the roles of non-governmental organizations (NGOs) in national development, human capital development and access to services in rural areas. Over 47,000 national and 200 international NGOs implement development projects on water and irrigation development in Nepal (Joshi, 2018) including HELVETAS (Swiss Development Organization), Mercy Corp, Water Aid, iDE, CARE, Oxfam, SNV and Winrock International. These actors collaborate with local NGOs and play roles in mobilizing resources, capacity building, and policy advocacy, water governance and multiple-use water systems (Khadka, Uprety, Shrestha, Minh et al., 2021). The Farmer Managed Irrigation System Promotion Trust (FMIST) is an important local NGO that organizes policy advocacy activities related to water resources and farmer-managed irrigation systems.

3.5.6. Bilateral and multilateral development partners

Over 13 bilateral and multilateral development partners are involved in irrigation, WASH and water resources development in Nepal. The World Bank and Asian Development Bank (ADB) are actively involved in large-scale infrastructure projects in the irrigation sector. In addition to USAID, the Swiss Agency for Development and Cooperation (SDC) is implementing a small-scale irrigation project anchored in local governments in the Eastern Hill regions. Other development partners involved in agriculture, water, sanitation and hygiene (WASH), climate change adaptation (including non-traditional irrigation technology such as dripi irrigation and multiple-use systems) in Western Nepal are IFAD, ACIAR, Finland, European Union, and the UK's FCDO (Khadka, Uprety, Shrestha, Minh et al., 2021).

3.5.7. Research institutions

The main national academic and research institutions of water resources and agriculture in Nepal include Tribhuvan University, Kathmandu University), Agriculture and Forestry University, and affiliated institutes working in different regions of the country. CGIAR, a global research partnership for food security, adds value on the ground through capacity building, and state-of-the-art research into transforming food, land and water systems in a climate crisis. Among them, International Water Management Institute (IWMI), CIMMYT and the International Rice Research Institute maintain country offices in Nepal. The CGIAR institutes provide state-of-the-art research capacities to develop solutions and innovations for smallholder farming systems ranging across varietal improvements, agronomy, mechanization, agri-business, value chain development, water resources research, and evidence-based policy and capacity development. CGIAR can substantially support evidence-based planning, implementation, monitoring, and impact assessment for irrigation development. The Commonwealth Scientific and Industrial Research Organization, an Australian Government agency responsible for scientific research, also implements water-related research projects in Nepal in collaboration with national and international partners. International Center for Integrated Mountain Development, an intergovernmental organization, implements research programs on water, mountain ecosystem services, climate change, livelihoods, and related thematic areas in the Hindu Kush Himalayan region countries, including Nepal.

4. Bio-physical and technological enablers

4.1. Water resource assessments

4.1.1. General overview of water resources in Nepal and study area

Nepal is a relatively water-abundant country with an estimated 210 km^3 total annual renewable freshwater resources and 7142 m^3/year in per capita terms (FAO, 2020). On a global level, this puts Nepal in the top 50 countries in terms of water availability. Statistics on groundwater are scarce, but groundwater resources are assumed to account for 10% of total renewable water resources, with surface water accounting for the remaining 90% (S. R. Shrestha et al., 2018). With irrigation being the largest water user (98% of total water withdrawals), the share of water withdrawals stands at 4.7% of water availability. The key challenges, however, lie in the variability of Nepal's water resource flows both in time and in space. Around 80% of precipitation and runoff occur during the monsoon months of June to September, recharging the river beds, soils, wetlands and groundwater resources (which are often severely water-limited during the dry season) traversing the hills and Tarai before exiting the country in transboundary water flows. The intensity of these monsoonal flows (and the lack thereof during the dry season) poses a key challenge for supply-side water management. As a result, only an estimated 39% of Nepal's cultivated land has some type of access to year-round irrigation. In addition, several economic and bio-physical constraints often make it hard for farmers to fully utilize the available water for resilient and sustainable agricultural production, both during the monsoon and in the dry season (V. P. Pandey et al., 2021; Urfels et al., 2020b, 2021).

4.1.2. Irrigation development in the FtF Zone

Nine major water management and development projects have been recently implemented or are ongoing in the Nepal FtF zone, highlighting the importance of water management to a large range of stakeholders. Officially, the irrigation schemes cover 310,260 ha of designed command area, but private groundwater irrigation contributes significantly to ongoing irrigation (V. P. Pandey et al., 2021). Recent data indicate that more than 40% of farmers use groundwater as their primary irrigation source and more than 30% of farmers intend to invest in groundwater irrigation (Urfels et al., 2020b). However, the level of groundwater and surface water use varies strongly across districts, highlighting opportunities for improving the use and management of the conjunctive use of groundwater and surface water in the FtF zone for sustainable water resources management. At the same time, data gaps on irrigation infrastructure and their use constitute a critical bottleneck for adaptive and sustainable water management (V. P. Pandey et al., 2021).

4.1.3. Water availability and demand in the FtF Zone

As in Nepal, surface water availability is generally with river discharge ranging from average 47 m^3 $second^{-1}$ in the Tila river to 3057 m^3 $second^{-1}$ in the Karnali river (Risal et al., submitted for publication). Most of the rivers are largely rainfed with a proportion of meltwater feeding the largest ones and groundwater contributing to baseflows in the dry season (Pandey et al., 2021). Soil and Water Assessment Tool (SWAT) model simulations confirm that physical surface water availability is not a limiting factor for monsoon season agriculture, as even the most intensive irrigation scenarios require less than 12% of streamflow, for example in the West Rapti watershed (Risal et al., submitted for publication). The same accounts for monsoon season groundwater, as monsoon precipitation and streamflow are generally sufficient to recharge shallow groundwater tables (Risal et al., submitted for publication). However, the largest water requirement occurs at the start of the season and is critical for agricultural system productivity (Urfels et al., 2021). In the monsoon season, the challenge lies in availability of water at the right time and in overcoming the technical and economic constraints for water distribution and access.

In the dry season however, water availability is generally low and increased water use will likely impact other water users and ecological requirements. For example, groundwater is the main water source for people and ecosystems in the dry season and also contributes baseflow for most rivers (S. R. Shrestha et al., 2018; Urfels et al., 2020b). Our simulations suggest that broadly increasing groundwater use after the monsoon recedes is likely to decrease groundwater levels from around 4 m below ground level to up to 6 m below ground level for more intensive irrigation intensification scenarios (Risal et al.,submitted for publication). The sustainability and consequences of such groundwater level declines depend on various factors including the current status of aquifers, types of affected ecosystem, socio-economic capacity, and aquifer characteristics. However, a drop of shallow aquifers beyond 10 m below ground level generally triggers a tipping point where severe social-ecological consequences may occur, highlighting the risks of increased groundwater use in Nepal's Tarai. At the same time, it can be expected that the response of groundwater to increased pumping will vary: the absence of reliable groundwater data makes it difficult to predict the impact for specific sub-regions and zones.

Another concern are future changes in groundwater recharge. The majority of groundwater recharge in the Tarai is assumed to take place in the Bhabar zone, a small stretch of land along the foothills of the Himalayan mountain range with good infiltration characteristics. Additional recharge comes from seepage across the Tarai, including paddy cultivation, wetlands and rivers. However, the clear demarcations of recharge zones and attribution of different recharge sources as a share of total recharge are yet to be identified. Simulations suggest that recharge may increase by 25% to 30% for most of the Tarai due to climate change. The climate change analysis used the NOAA_RegCM4 model, which is widely used for South Asian countries, although use of a different model may provide a different estimate on groundwater recharge (as is the case in most climate change analysis, it is important to note that using climate projections from a different model may provide a different estimate). In addition, improved land management in the Churia range and Mid-Hills may further an increased recharge, with benefits for both groundwater in the Tarai and revitalization of springs in the Mid-Hills.

Altogether, the simulated scenarios suggest that increasing agricultural productivity and resilience through groundwater irrigation may have minimal social and ecological negative externalities for low- and medium-use scenarios, if these are paired with stringent monitoring and conservation policies that inform geographical targeting. Strengthening groundwater data assets and the science–policy interface for groundwater characterization, early-warning systems, and advancing groundwater modeling that makes the invisible visible are thus critical for sustainable and resilient irrigation management in Nepal's FtF zone.

4.1.4. Challenges and opportunities

From a resource standpoint, Nepal's FtF zone harbors significant opportunities for increasing resilience through improved irrigation development and water management. The challenge lies in distributing water resources in time and space, and adapting farming systems to the challenges of water distribution and rainfall variability. Most districts offer some areas where canal irrigation systems are designed to provide irrigation with a low cost for farmers, ranging from 16% to 50% of cultivated area. However, addressing challenges in year-round operation and maintenance of canals and service orientation of the irrigation bureaucracy favor the conjunctive use of groundwater and requires enhanced coordination with agricultural development programs and strengthening the service orientation of canal irrigation officials.

Groundwater irrigation provides by far the largest potential for improving farmers' access to water resources to bolster their resilience to climatic variability and change. Challenges posed by aquifer heterogeneity and the high cost of pumping can be addressed through clever data collection and low-cost hydrogeological field research, alongside strengthening of the private irrigation sector to develop innovative, lower cost and more efficient pumping technologies. Precise data on the spatial distribution of groundwater potential zones are absent, but previous studies estimated that up to 80% of cultivated land is suitable for groundwater irrigation. Better understanding of spatial zones, temporal variation, and response to increased pumping or recharge is required to develop assessments of groundwater potential zones. Additional hydrogeological studies and digitizing previous reports and groundwater studies and making them openly available would be an invaluable asset. In areas with unsuitable shallow aquifers, using innovative methods for increasing the inclusive access to private deep tubewells should be complemented by targeting support for farming system diversification that suits the available water requirements. Lastly, the impact of climatic change on water resources availability remains poorly understood and adaptive management is required to adjust sustainable irrigation planning to evolving changes in ecological boundaries.

4.2. Knowledge and capacity in regard to agricultural water management

While there has been much research in Nepal into the availability of water for irrigation, accessibility of irrigation water, and irrigation system management (sections 4.1 and 4.3), very few efforts have been put into scaling up research into field-level agricultural water management practices. This section of the framework therefore focuses on field-level agricultural water management and learnings from past research.

The main threats to the productivity and sustainability of the rice–wheat cropping system in Nepal are (1) inefficient use of inputs (fertilizer, water, labor), (2) increasing scarcity of resources, especially water and labor, (3) fast-changing socio-economic conditions, and (4) changes in land use (cropping practices and cropping systems) driven by a shortage of water and labor (Ladha et al., 2009). It should also be noted that the agricultural technologies which have been promoted for the last twenty years or more (that is, before 2009) have been imported from more highly developed nations, where they were developed for larger farm sizes and therefore not necessarily suitable for Nepal (Manandhar et al., 2009). For small farming households in Nepal, labor is cheap and capital expensive, so appropriate technologies targeting poor and marginal farmers need to fit small farm sizes and be priced accordingly. In addition, agricultural extension agents need to be well-trained and well-informed, enabling them to pass up-to-date knowledge on to farmers. The CSISA Activity has achieved a great deal of scale-appropriate mechanization over the last ten years, providing access to appropriate technology for the small farmers of Nepal.

Investments in improvements in irrigation efficiency[1] at the field level have been pale in comparison with investments in irrigation infrastructure. The majority of irrigation methods used in Nepal are flood-based or furrow irrigation. These are the most inefficient methods of irrigation, with efficiency of only 60% to 70% (Doorenbos & Pruitt, 1977), and reportedly assumed at only around 60% for Nepal's western region (Pakhtigian et al., 2020). Improvement in irrigation efficiency can be achieved by upgrading irrigation systems, as well as incentivizing farmers to implement efficient irrigation systems.

Conventionally, rice is sowed by transplanting after puddling the soil. This requires a very large amount of water which leads to poor water-use efficiency because of water loss (due to seepage through the soil profile) as well as a higher rate of evaporation (Mandal et al., 2009). Wheat is grown during the dry (winter) season from November to April. Late planting of wheat due to the late harvest of rice and extensive tillage for field preparation by farmers can cause a linear decline of the yield of 1% to 1.5% per day (Mandal et al., 2009). The possible cause of yield reduction is related to high temperatures around heading, reductions in pollen viability resulting in a reduced number of grains per head, and reduction in the length of the grain-filling period (Marhatta et al., 2018; Ortiz-Monasterio R. et al., 1994). A number of improved land and crop management technologies popularly known as resource conserving technologies have been developed and disseminated in Indo-Gangetic plains which can be tested in the broader area (Ladha et al., 2009). These technologies include laser land leveling, zero- and reduced-till, drill-seeded wheat, direct seeding of rice with intermittent irrigation (alternate wetting and drying), and a leaf color chart for nitrogen management.

In the experiments done at the field level, zero-tillage direct-seeded rice required up to 40% less irrigation water than the traditional puddled transplanted rice (Ladha et al., 2009). For the similar experiment at the field level for wheat, results indicate that water savings were positive for zero-till wheat, probably due to timely planting. Also, laser-leveling increased wheat yield by 0.4 t per ha and net income by USD95 per ha with savings of 35 mm in total water. In a similar experiment with early seeding of rice using dry-seeded rice establishment, the pre-monsoon and early-monsoon rains helped the crop during the seed emergence and vegetative growth stages, consequently saving more than 75% in irrigation water (Mandal et al., 2009). Although these resource conserving technologies have shown possible benefits to farmers, adoption is rather poor because of inadequate dissemination activities, as well as the inability of poor farmers to access and apply them in their small and scattered fields (Mandal et al., 2009). In similar research done by IWMI, conservation agriculture (strip and zero tillage) was viewed as a relatively new frontier in adapting to water stress and was able to reduce irrigation costs by 50%; however, the difficulties in supplying high quality labor-saving equipment are seen to be a critical barrier (Schmidt et al., 2019).

Shifting from one crop to another or changing the crop variety has also been a method by which to use irrigation water efficiently and economically. Experiments conducted in the Southeast Tarai region of Nepal showed maize to be the most water- and energy-efficient crop, requiring almost half of the resources used in wheat production for each ton of yield (S. Shrestha et al., 2015). This also concluded that under current practice it would be wise to shift from wheat to maize, which would not only increase the benefits per unit area but also improve the productivity of the resources used. Other research, carried out in Kapilvastu district, found that farmers replaced the traditional, long duration indigenous rice variety with shorter duration varieties in response to the shortening of the monsoon season (Bhandari, 2013). They also stopped growing cereals and started cultivating groundnut, peanut and watermelon during the monsoon, and sweet potato in the winter in the *bagar* (riverside) lands. Although there has been no comparative study in Nepal, replacing cereals with vegetables using a potentially efficient irrigation system such as drip irrigation can be quite beneficial to farmers. A comparative study done in Bangladesh showed that compared to the total cost for rice, gross benefits and gross income for potato were 59%, 128% and 326% higher respectively (Schmidt et al., 2019). However, it should be noted that crop diversification and substitution contain more risk for smallholder farmers, as local markets are plagued by inequality between farmers and buyers, which translates into low purchasing prices, as well as price instability in the local market and the market value chain which has not reached its full potential (Schmidt et al., 2019). Crop diversification and substitution are more prevalent among larger and medium farmers, as they have more land and investment capacity. The benefits of shifting crops should be communicated to farmers in different mediums, encouraging them to adopt such practices – otherwise, these research outcomes and anecdotal evidence may not translate into results.

In Mid-Hills regions, water harvested during the monsoon season can be used for supplementary irrigation of vegetable crops with efficient, sustainable irrigation systems (Manandhar et al., 2009). The low-cost drip irrigation technology developed through research and development has already been used by more than 5000 farmers in the hilly regions of Nepal to successfully generate income through vegetable cultivation. Drip irrigation means that fields can be irrigated using less water, making it more appropriate for areas with water scarcity. A case study conducted at the community level showed that the increased use of this kind of technology shifted cropping patterns from cereals to off-season vegetables, as well as increasing (1) cropping intensity

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[1] The irrigation efficiency for the field can be defined as water applied into the field which is used effectively by the plants. Irrigation methods with efficiency equal to or higher than 75% such as sprinkler irrigation are considered efficient methods of irrigation (Brouwer et al., 1989).

by 100%, (2) crop productivity, (3) farm income by 30% to 40%, and (4) off-season farm employment by more than 50% (Bhattarai, 2008). However, it should also be noted that if these systems are not well-installed and well-maintained, their performance and efficiency can be poor. In addition to system design factors, the technical capacity of local farmers, field topography, socio-economic capacity and soil hydraulic properties should also be assessed before installing this kind of system (Schmidt et al., 2019). Training farmers, the increase in technical capacity of the local community and in socio-economic access, along with knowledge-sharing about the advantages of these new systems compared to traditional irrigation should go hand-in-hand with an introduction to new technologies to safeguard their long-term sustainability.

4.3. Sustainable and inclusive operation and management of irrigation infrastructure

There are three major types of irrigation infrastructure in Nepal: canal irrigation, deep community tubewells and shallow private tubewells. Although there is an increasing number of deep private tubewells, and group ownership is required for shallow tubewell subsidies, these are rare in practice as costs are prohibitive and elite capture of subsidies frequent (Urfels et al., 2020b). This section discusses the challenges to and opportunities for sustainable and inclusive operation and management of the different infrastructure types of tubewell, presented in ordered of size of their typical command area and thus decreasing complexity of challenges in terms of operation and management.

4.3.1. Canal irrigation

Canal irrigation schemes in Nepal are often subdivided into three different categories depending on their institutional setup: farmer-managed irrigation schemes (FMIS), government agency-managed irrigations schemes, and jointly managed irrigation schemes (V. P. Pandey et al., 2021). However, their boundaries are blurred, with WUAs having varying degrees of influence on the operation and management of irrigation schemes, and enjoying different levels of support from government agencies (Khadka, Uprety, Shrestha, Minh et al., 2021). Despite mandates to include women on the boards of WUAs, their participation is often procedural with no significant potential to shape decision-making (Khadka, Uprety, Shrestha, Minh et al., 2021; Udas & Zwarteveen, 2010). Moreover, landless tenants and sharecroppers, a majority of whom are women and from the Dalit community, and who sustain farming systems in Nepal, are excluded from WUAs (S. Shrestha & Uprety, 2021). Training opportunities and services such as agriculture training are targeted at farmers with land ownership, rendering landless women and Dalit farmers disadvantaged in terms of the knowledge and information imperative for scaling, adaptation and improved age management of water for irrigation. This institutional complexity is among one of the key challenges for improving irrigation management and operation in Nepal. Different social, technical and geographic conditions require contextualized responses in the institutional setup. However, unclear responsibilities and coordination mechanisms discourage sustainable management practices and often disempower already disadvantaged groups lacking the social capital to mobilize internal or external resources for adequate operation and maintenance (Khadka, Uprety, Shrestha, Minh et al., 2021), leading to dissatisfaction and conflict which promote typical build–neglect–rebuild cycles (Pradhan & Belbase, 2018). Unreliable linkage of WUAs to agricultural value chains, knowledge and service providers further limits the returns on investment in canal irrigation schemes.

In addition, the topographical characteristics of the FtF zone further complicate the management and operation of canal irrigation schemes. The surge in streamflow with the start of the monsoon season frequently damages the headworks of canal irrigation schemes which then require frequent and costly maintenance (V. P. Pandey et al., 2021; Pradhan & Belbase, 2018). Furthermore, high sediment loads strongly reduce the carrying capacity of canals if they are not annually dredged. At the same time, increasing labor scarcity due to migration and the monetization of the rural economy increases the cost of such labor-intensive maintenance activities which used to be conducted with the help of in-kind contribution of WUA members (Pradhan et al., 2017). In addition, the water supply through canal irrigation schemes is often limited at the time of rice planting when water levels in the river are still low at the start of the monsoon, as well as the dry season when streamflow recedes to significantly lower levels compared to their peak flows. With storage options being limited, conflict over the just and equitable distribution of the available surface water resources is therefore difficult to avoid, as canals are generally designed for water delivery during the high flow months (Khadka, Uprety, Shrestha, Minh et al., 2021; V. P. Pandey et al., 2021).

Altogether, successfully addressing these challenges requires a shift in perspective regarding the development, modernization and management of surface water irrigation schemes. Instead of focussing on infrastructure expansion and increasing water use efficiency, more farmer-centric attention is needed to providing inclusive and climate resilient water services. This shift in mindset helps irrigation programs to cater to farmers' needs through coordination of public and private institutions (Khadka, Uprety, Shrestha, Minh et al., 2021; Pradhan & Belbase, 2018). Within this framework, several options have been identified to accelerate change in Nepal's canal irrigation sector:

1. First, existing irrigation schemes need to be strongly linked to development programs in agriculture along the entire value chains including improved supplies and better market

integration. For example, WUAs and irrigation agencies can become integral stakeholders of ongoing agricultural development programs and may align with existing agricultural cooperatives to better coordinate water delivery services with market opportunities.

2. Second, irrigation management requires a water resources management perspective that explicitly accounts for, targets, and invests in opportunities for women, marginalized (e.g. Dalit, landless and near-landless farmers) groups, and youth. Several opportunities exist to create jobs that leverage existing human capital and strengthen value chains, irrigation management, and markets. For example, constraints in labor availability can be addressed by strengthening rural networks of technicians that can use their machinery to help with work such as dredging operations and headwork reconstruction. At the same time, financial and human capital of returnee migrants may be mobilized to build agro-irrigation value chains that are required for the cultivation, processing and marketing of high value products.

3. Third, policy processes and dialogues need to align support mechanisms and capacity building for water services through streamlining coordination across multi-sectoral institutions and the newly established three tiers of government (local, provincial, federal). Local, multi-stakeholders and media-supported water dialogues could facilitate mainstreaming of GESI issues into water-related debates and highlight contextually relevant issues in water management. Integrated water management mechanisms from local to federal level could then stream this information to higher-level decision-making bodies through cross-sectoral water dialogue platforms in an effort to strengthen the adaptive management of the water bureaucracy.

4.3.2. Deep community wells

Deep community tubewells are electrically powered wells with command areas of ca. 25–50 ha. TheGovernment of Nepal has provided many deep tubewells to communities in the Tarai, especially in the 1980, and 1990s (Pathak, 2018; S. R. Shrestha et al., 2018). Deep tubewells are generally powered by 20–35 HP submersible pumps and have significantly higher discharge rates of 25–40 l/s compared to 6–12 l/s for shallow tubewells with 3–7 HP pumps. However, many of these wells have ceased functionality due to constraints in irrigation fee recovery to support repair and maintenance (Urfels et al., 2021). The reasons for failure and success of these deep tubewells are not well-documented, but anecdotal evidence suggests that a combination of water user group leadership characteristics and ability to collect irrigation fees (or lack thereof), neglect and interruption of technical support in times of political instability, general safety concerns such as theft, and elite capture have contributed to the failure of most deep tubewells. In addition, deep tubewells suffer from the similar coordination problems with value chains, markets, and trainings as canal schemes, while water distribution is also prone to conflict as a full rotation of the full command area typically requires at least two weeks (Urfels et al. 2021). Delays for farmers who receive water last are particularly significant, as who receive water last as two weeks of water stress can significantly impact production during water-sensitive crop growth stages. Although fewer electrically powered deep tubewells are currently commissioned, solar powered deep tubewells are gaining increasing attention (S. Shrestha & Uprety, 2021). From an operation and maintenance perspective the challenges and opportunities are very similar to those of canal irrigation schemes, programs for which should be extended to include deep tubewells for activities such as multi-sectoral coordination and trainings, generating inclusive jobs across the agro-irrigation value chains, and multi-stakeholder water dialogues.

4.3.3. Shallow private wells

Lastly, shallow tubewells are currently the most popular type of irrigation infrastructure, and with farmers stating strong interest in investing in shallow tubewell irrigation technologies are likely to remain the primary source of irrigation for the foreseeable future (Urfels et al., 2021). Operation and maintenance of shallow tubewells is comparatively simpler than for deep tubewells or canal irrigation schemes. For shallow tubewell operation and maintenance, the key issues are best dealt with at the time of well location siting and drilling (Danert, 2015). The use of appropriate well siting can strongly prolong the lifetime of a well and ensure highest possible recharge and water quality (Danert et al., 2020). However, currently no strong well-drilling association or training programs exist, thus providing a useful investment opportunity. with strong overlap with the WASH sector as described and further elaborated in sections 3.4 and 3.5. In addition, the diesel pump that most farmers use for irrigation requires frequent repair and maintenance (Urfels et al., 2020b). Strengthening these supporting industries and availability of spare parts is thus critical for smooth operation and is further discussed as part of the irrigation value chains in section 3.3. Furthermore, most farmers do not own pumps but rent them from other farmers who are often reluctant to provide rental services due to constraints in labor availability (Urfels et al., 2020b). In most areas, pump owners are expected to provide a package of irrigation services including transport and operation, which often interferes with the owners' farming operations and other income-generating or leisure activities, or leisure activities, leading to high rental prices. Addressing these issues by reducing the pressure on the rental market by increasing farmers' pump ownership through improved pump selection or by better coordinating rental services (e.g. by pooling land that is closely related into the same irrigation session) may decrease delays in irrigation timing.

5. Case study: the Babai watershed

This chapter provides an overview of how a framework for sustainable and inclusive irrigation development can be applied to guide decision-making at the watershed level. The governance, socio-economic, bio-physical, and technological enablers elaborated upon in sections 3 and 4 provide guardrails and a basket of options for catalyzing inclusive and sustainable irrigation development across Nepal. For small-scale irrigation, most convening and implementing power is vested with local government, which requires focussed capacity-building efforts. Irrigation development interventions must therefore coordinate across scales to provide local government with the capacity for supporting inclusive and sustainable irrigation development efforts. These need to be tailored to household needs and targeted across social-ecological zones of their watershed, synergizing with existing agricultural development efforts, resource endowments, and economic opportunities.

The Babai watershed is chosen as an example because it (1) covers both hilly and Tarai districts, (2) features a major canal irrigation scheme plus groundwater irrigation, and (3) has frequently experienced climate shocks. This case study starts with a summary of the Babai watershed's key biophysical and socio-economic characteristics and presents the key output of SWAT model simulation (for details and methods see Appendix and Risal et al., submitted for publication), which assess the bio-physical water resources endowments and irrigation demands across alternate future scenarios. This chapter uses the SWAT model as a tool for the assessments; however, other similar modeling tools can be used for similar assessments. The chapter then discusses major inclusive and sustainable irrigation development opportunities, with a key focus on cross-scalar interaction including the implementation of federalism, upstream–downstream linkages, and GESI principles.

5.1. Characteristics of the Babai watershed

Babai watershed (332,916 ha) covers Dang, Salyan and Bardiya districts of Lumbini province in Nepal (Figure 4). The watershed is drained by the Babai river, extends from the upper Dang valley to the lower Babai valley, and has an elevation range from 52 m to 2798 m above mean sea level. About 60% of the watershed area is covered by forest and about 30% by agricultural lands. The maximum streamflow at the watershed outlet was 236 m^3/sec during the monsoon season and the minimum streamflow was 7 m^3/sec during the pre-monsoon season. The annual water availability of the watershed is 3161 million m^3. The watershed's average annual rainfall is 1400 mm, with 80% of the rainfall occurring in the months from June to September (Mishra et al., 2021). The temperature ranges from a maximum daily temperature of 32°C in May to a minimum of 7°C in January (Figure 4). The rain- and spring-fed Babai river originates in the Siwalik hill region (Churia range) in the North and drains towards the Ganges river in the South. The Churia range extends along the foothills of the Himalaya mountain range, covering about 12% of the total land area of Nepal, and taking an important role in the conservation of the surface and groundwater source of the Tarai, while the river supplies water to bio-diverse ecosystems downstream. The greatest proportion of agricultural land is classified as lowland dominated by rice production, which is preceded by wheat as the additional crop of the year. Importantly, maize and legumes are commonly grown in higher-lying, well-drained areas, and many households grow vegetables and fruit trees in their gardens. Because Dang is situated in a strategic place along major trade and transportation routes in Lumbini Province it has good potential for commercializing agriculture.

Economically, agriculture is the dominant sector in the Babai watershed, but low levels of agricultural productivity and income hamper the sustainable development of the region. Inadequate irrigation facilities pose a key barrier to reducing climate risks and increasing productivity, while increasingly erratic and highly seasonal rainfall frequently causes flooding and drought – limiting the effectiveness of conventional irrigation development. The Babai Irrigation Scheme seeks to irrigate 36,000 ha of agricultural land in Bardiya district by 2023 and has been listed as a project of National Pride by Nepal's National Planning Commission. Similarly, several small irrigation schemes have been planned in Dang. However, the designed command areas of these schemes are unlikely to be fully and equitably served, as experience in other irrigation schemes has shown. Besides, supplementary irrigation is likely to be required in areas where the canals do not reach upland fields or water delivery is untimely. Conjunctive use of surface and groundwater is therefore crucial for enhancing the agricultural productivity and resilience of the watershed.

5.2. The modelled irrigation development scenarios

Different scenarios were developed in a participatory approach through stakeholder workshops that explored the likely and desired agricultural development pathways and evaluated based on key sustainability and crop production indicators. Two optimistic irrigation development scenarios were simulated and evaluated:

(a) Rice–vegetable–rice: an optimistic scenario of adequate year-round irrigation in the Tarai where irrigated rice–wheat is replaced monsoon rice that is followed by a short vegetable crop and another rice crop in the spring, and

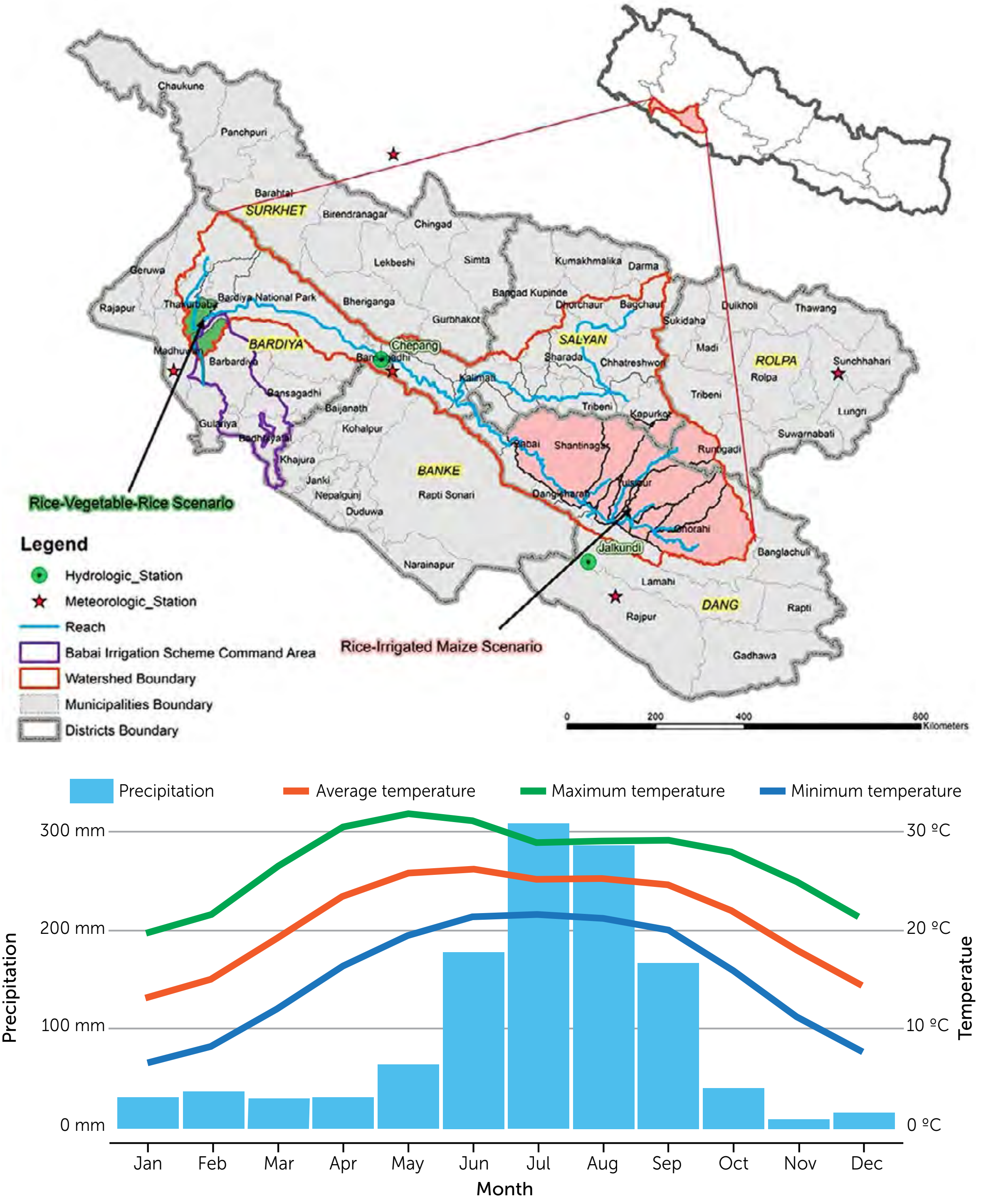

Figure 4. Top: location of the Babai watershed, and areas where scenarios were implemented. Bottom: average monthly minimum, maximum and average temperature and precipitation of Babai watershed.

(b) Rice−maize: expanding irrigation into the dry season and thus replacing monsoon irrigated ric−-lentil with fully irrigated rice−maize in the Dang valley.

The use of both surface and groundwater irrigation and conjunctive use was evaluated, with groundwater sustainability focussing on both long-term depletion and annual recharge, and surface water sustainability focussed on comparing withdrawals with discharge across seasons.

Lastly, the impact on agriculture was assessed by comparing crop yield and total crop production across scenarios. Importantly, due to insufficient data availability, the model only accounts for local groundwater recharge from rainfall and ignores regional recharge patterns and recharge from surface water. The model outputs are thus very conservative and only indicative of potential risks, rather than providing the full picture.

5.2.1. Groundwater recharge and irrigation demand

Surface irrigation generally replenishes groundwater resources, while groundwater irrigation depletes them. Surface water irrigation increased groundwater recharge by 13% to 16% for the rice–vegetable–rice scenario and 8% for the rice–maize scenarios. The model results further suggest that groundwater reserves are sufficient to irrigate dry season crops if the monsoon crop is irrigated with surface water. For example, the Thakurbaba and Barbardiya municipalities of Bardiya districts may utilize water from Babai Irrigation Project during monsoon such that groundwater can be preserved during the monsoon and only withdrawn during the dry season. However, if monsoon rice is also irrigated with groundwater the model outputs suggest that water abstraction may become unsustainable as only 48% to 52% of crop water requirements may be fulfilled with local groundwater recharge (Table 2). The same pattern can be found in the rice–maize scenario in Dang, where the original rice–lentil systems is largely sustainable (even if rice is irrigated with groundwater), but care must be taken when fully irrigating rice–maize with groundwater throughout the area as only 61% to 81% of the area can be fulfilled with local groundwater recharge (Table 2).

Table 2. Percentage of total agricultural land that can be provided with groundwater irrigation sustainably for rice–wheat, rice–vegetable–rice, rice–lentil and rice–irrigated maize, implemented within the Babai watershed.

Year	Rice–wheat	Rice–vegetable–rice	Rice–lentil	Rice–irrigated maize
2000–2020	64	48	139	61
2021–2035	64	51	195	81
2035–2050	62	52	183	77

These results suggest that there are large opportunities for gaining access to dry season irrigation through efficient use of groundwater. This can provide opportunities for irrigated agricultural value chains of field crops and high value vegetables and other cash crops (e.g. spices, horticulture, medicinal herbs, maize) that may directly target women and marginalized groups with links to markets and farm machinery programs of the PMAMP (Foster et al., 2021; Sugden et al., 2020). Importantly, the results highlight the value of conjunctive use planning. To achieve this, irrigation development needs to address the technocratic and masculine perspectives and approaches which dominate in public water institutions (G. Shrestha & Clement, 2019; Udas, 2014) to strengthen gender-sensitive and socially inclusive irrigation governance and irrigated agriculture value chains, including markets for agriculture and irrigation technologies.

5.2.2. Impact of scenarios on long-term groundwater reserves

The SWAT model uses a coarse approach to assessing groundwater dynamics, and outputs should be considered as relative indicators – not as absolute numbers. The average decrease in groundwater for the rice–wheat baseline scenario was 10 mm from 2020 to 2050, while the average decrease during the rice–vegetable–rice scenario was only 4 mm in Bardiya district in the southeastern part of the watershed (Figure 5). They indicate the directionality of the impact of increased groundwater use; however, estimating the true impact requires better data resources. Nevertheless, these results do suggest that conjunctive use planning for irrigated agriculture can avoid the long-term depletion of groundwater resources. Importantly, they also suggest that with intensified groundwater use, seasonal depletion will increase, leading to lower groundwater tables in the dry season. For example, wildlife conservation in Bardiya National Park partially depends on groundwater, and ongoing investigations on these linkages between agriculture, the water system and wildlife conservation should be conducted and considered in irrigation development.

For the rice–lentil and rice–maize systems, a 50 mm and 52 mm increase in groundwater levels was observed from 2020 to 2050 in downstream locations within Dang district (Figure 5). Analysis of the climate change scenario showed a 45 mm increase in groundwater levels. This suggests that both rice–lentil and rice–irrigated maize cropping systems are unlikely to experience long-term groundwater depletion, especially as recharge is set to increase due to increased precipitation driven by climate change. These results indicate an opportunity for scaling new dry season cropping systems that are linked to irrigation management, conjunctive use of surface and groundwater, markets, and digital technologies. The use of small pumps for efficient use of water during dry season can also enable farmers, especially women and smallholder farmers, to produce high value vegetable crops and connect with markets and public institutions (Schmidt et al., 2019) (Sugden et al., 2020).

5.2.3. Impact of upstream scenarios on irrigation sustainability of downstream area

An analysis of upstream and downstream groundwater interaction provides another important lens for assessing the sustainability of ground and surface water for irrigation. In general, the model outputs suggest that upstream surface water irrigation in the monsoon season is likely to increase water availability downstream by ca. 10% due to increased groundwater recharge and discharge to rivers. However, as pointed out in section 5.2.2., the opposite is true for groundwater

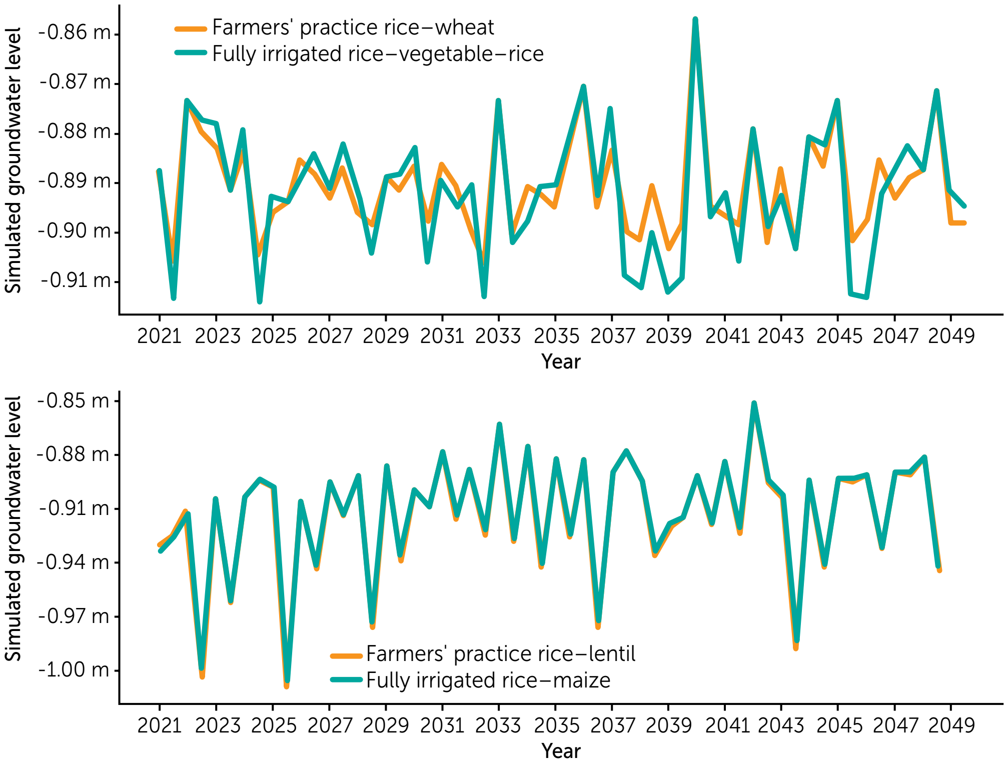

Figure 5. Simulated groundwater fluctuations (indicative of trends) for rice−wheat and rice−vegetable−rice, implemented in Bardiya (top) and for rice−lentil and rice−maize implemented in Dang (bottom).

abstraction in the dry season. This strongly reduces dry season streamflow by an estimated 14%, indicating potential risks of increased dry season groundwater abstraction on riverine ecosystems, while surface water irrigation is not possible as base flow is too low (Figure 6). Again, these estimates are only indicative as the underlying data assets need strengthening for more accurate participatory assessments; adequate monitoring is the best bet for ensuring that irrigation development stays adaptive and within ecological boundaries.

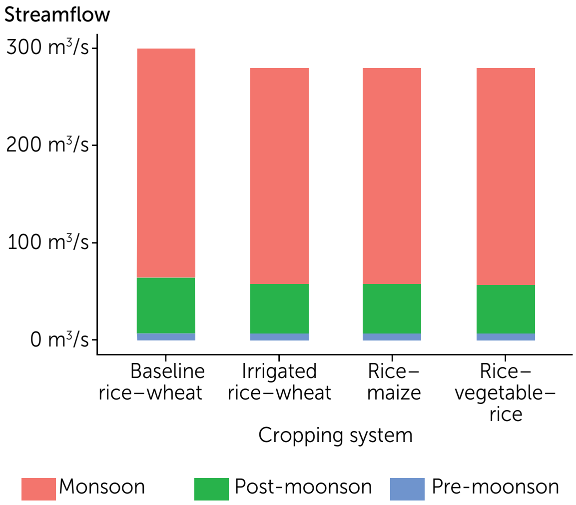

Figure 6. Average seasonal streamflow during pre-monsoon, monsoon and post-monsoon seasons for different scenarios.

For example, the average streamflow for the rice-wheat baseline scenario as measured at the outlet of the watershed were 236 m^3/s (monsoon), 57 m^3/s (post-monsoon) and 7 m^3/s (pre-monsoon). The rice−vegetable−rice scenario reduced this number to 222 m^3/s (monsoon) and 50 m^3/s (post-monsoon). The 57 m^3/s and 7 m^3/s during the post- and pre-monsoon season were not sufficient to support surface water irrigation. However, groundwater irrigation led to a reduction in the post-monsoon season discharge. The average flow during monsoon season was reduced by 6% when surface water was withdrawn from the river to irrigate monsoon season crop (rice), in both the rice−vegetable−rice scenario and the rice−maize scenario.

Lastly, the model results suggest that irrigation development and climate change are likely to lead to higher rates of surface run off, which, if conserved adequately, may provide further water security. For example, climate change increased surface runoff by 19% to 30% in the near-term (2021 −2035) future, and by 32% to 45% during the mid-term (2035−2050) future period. This increased runoff presents both threats and opportunities – which can be addressed by inclusively engaging communities and the private sector to ensure adequate irrigation scheduling (e.g. through climate services) as well as water harvesting (e.g. through nature-based solutions such as wetlands and diversified agricultural systems).

5.2.4. Impact of scenarios on yield, production and economic value

Rice–vegetable–rice outperformed rice–wheat, while rice–maize was inferior to rice–lentil based on local price comparisons (Figure 7). However, the difference between future scenarios was small, suggesting that diversified systems of production are also attractive from an economic perspective. For comparison, we converted crop yields into rice equivalent yield based on local prices. For rice–lentil, the added benefits of improved soil fertility from legume cultivation and lower irrigation requirements further increase its benefits compared to the rice–maize scenario. Moreover, and especially under projected climate change scenarios, crop yield and production for winter and spring seasons were low even after sufficient irrigation and fertilizer were provided, because of a shortened growing period and temperature stress. These results indicated that sustainable irrigation development pathways need not only to be based on sufficient input, but that adaptation to changing temperature regimes is becoming increasingly important. Assessing which combination of field level interventions, planting time adjustments, and cultivar choices is best adapted to climatic conditions will be crucial to support irrigation development.

5.2.5. Farm type and canal irrigation projects in the Babai watershed

Farm type and size are also important considerations for targeting irrigation development, as full-time farmers have different investment capacities and risk preferences from part-time farmers (Gyawali, 2009), while production is also notably higher at the head end of canal schemes (Gyawali, 2009). The Babai Irrigation Project (BIP) is a combination of five FMIS and an extended government-managed canal irrigation system (Adhikari et al., 2009). The FMIS are run and built by farmers with little to no outside intervention and generally perform very well (Pradhan, 2000). Rehabilitating the existing FMIS – by building permanent diversion structures, canal lining, and adopting more efficient water management practices – could help modernize these systems (Adhikari et al., 2009). Sustainable irrigation development should cater to the varying needs of different farmers as well as the irrigation systems, with entry points for private, community and government-managed irrigation systems.

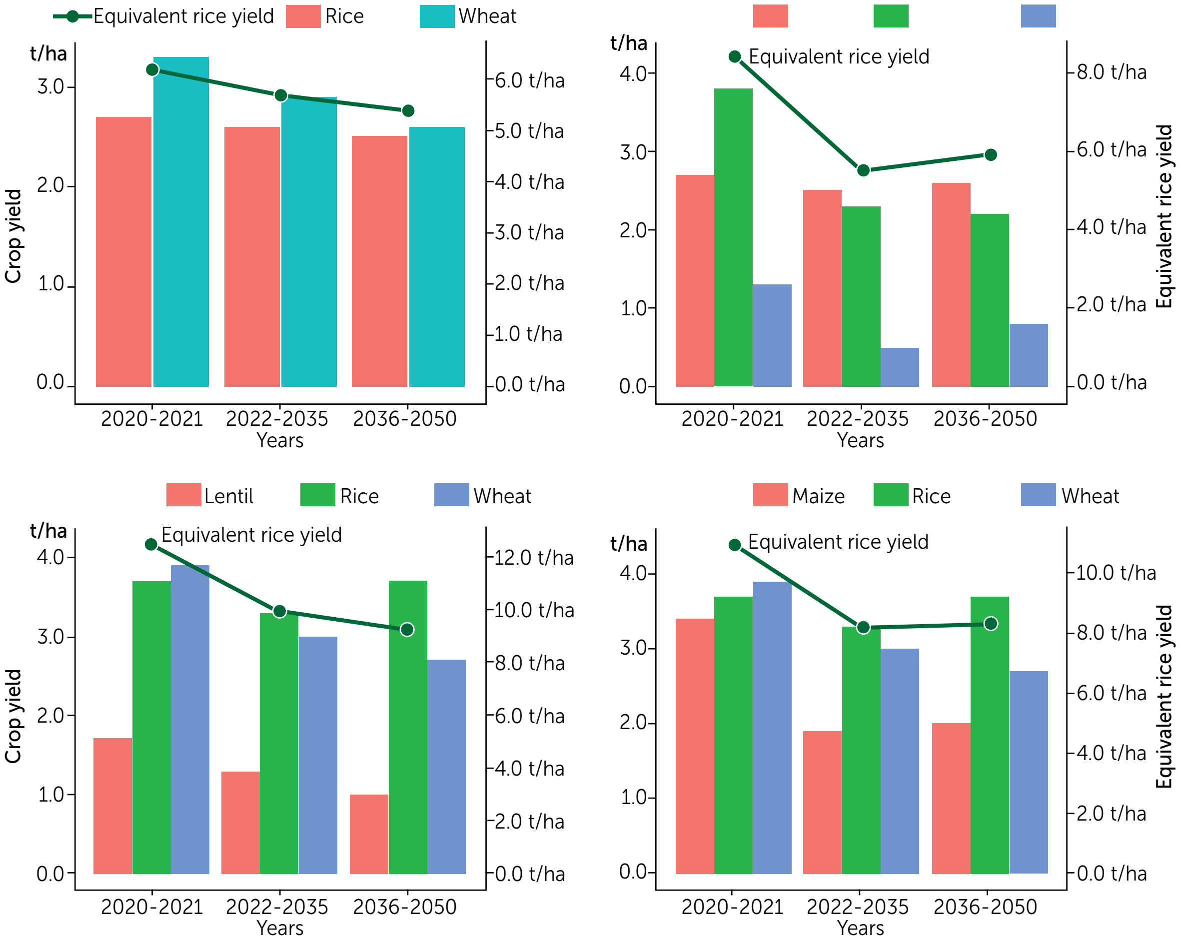

Figure 7. Top: Crop yield and rice equivalent for the rice–wheat and rice–vegetable–rice cropping system implemented in Bardiya district. Bottom: rice–lentil and rice–irrigated maize cropping system implemented in Dang district.

5.3. Implications for inclusive and sustainable irrigation development in the Babai watershed

This brief application of the sustainable and inclusive irrigation framework to the Babai watershed clearly shows that inclusive irrigation development together with various agricultural intensification and diversification scenarios can substantially contribute to increasing crop production in Nepal. However, neither streamflow nor groundwater can provide full and year-round irrigation for intensified cropping systems, and conjunctive use planning is required for an equitable and year-round irrigation supply. In addition, some results indicate that certain irrigation development pathways may risk negative environmental impact and better data and close monitoring is required to ensure ecological limits are not breached. Also, bio-physical constraints on irrigation development and use are further exacerbated by social and economic constraints, especially for marginalized groups, women and youth. Diversified and high value cropping scenarios are generally feasible from a water resource perspective but require explicitly pro-poor and socially inclusive investments and depend on markets and value chains. Vegetable and cash crop cultivation provide significant scope, providing returns on investment due to their larger revenue and relatively small land footprint, while irrigated cereal crops will remain crucial for reaching targets of food self-sufficiency. Coordination between provinces, local governments, different ministries and the private sector is required for sustainable irrigation scaling. The watershed passes through both Lumbini and Karnali provinces, and action upstream – for example, in Karnali province or Dang district – will have a strong impact on water availability in the Tarai (in Bardiya district, for example), especially in the dry season, requiring watershed– or basin–level coordination mechanisms.

Ensuring that irrigation investments promote inclusive and just growth within a safe ecological operating space entails several cross-sectoral investments across various tiers of government. The following specific recommendations provide a watershed-specific starting point for developing inclusive and sustainable irrigation investments, that need to be carried out in concerted and simultaneous action.

Irrigation development priorities in the Babai watershed should be to:

1. Develop irrigation through groundwater irrigation systems based on cost-effective and suitable pump choices (e.g. diesel, electric and solar systems) and water distribution arrangements that best suit farmers and value chains. Different systems may be used for Dang's upland maize systems and valley rice systems, Baridya's lowland rice systems, and high value crops, while also matching farmers' varying investment capacities.
2. Improve groundwater monitoring for early warning of groundwater depletion and the potential impact of climate change. Even with full annual recharge, groundwater table drops in the dry season may cause negative Social and ecological impacts such as the ability of farmers to use small irrigation pumps and households to access water for domestic purposes, or for ecological needs such as for forests and wildlife.
3. Conjunctive water use planning in the Babai and Dang irrigation schemes provide safe groundwater development areas that can improve the scheme productivity, especially if water management and WUA support is linked to better agronomic practices and focussed dynamically in the landscape and throughout the seasons.

6. Sustainable groundwater management in Western Nepal

This chapter provides additional technical background on key principles for sustainable groundwater management. These are a crucial complement to inclusive and sustainable irrigation development, as more than 50% of irrigation in the Western Tarai, especially small-scale irrigation, relies on groundwater.

6.1. Sustainable management of a hidden resource

The hidden nature of groundwater poses great challenges to its sustainable management, but intensifying groundwater use requires prompt action building on recent scientific advances. Groundwater harbors around 70% of global accessible freshwater resources (Lall et al., 2020) and many cities, wildlife, rivers, coastal areas, and especially agricultural production depend on it. However, intensifying water demand across sectors has already started to severely impact groundwater resources and flows in places such as the Northwestern Indo-Gangetic Plains, North China Plains, California Central Valley, and large parts of the Middle East and North Africa (Famiglietti, 2014). The effects of unsustainable groundwater management are multi-layered because groundwater occupies a central position in the hydrological cycle and is closely connected to various ecosystems. For example, surface water resources are either fed by groundwater resources if water tables are high enough, or recharge groundwater resources if the water table is below a critical threshold (Figure 8). In monsoon regions, the

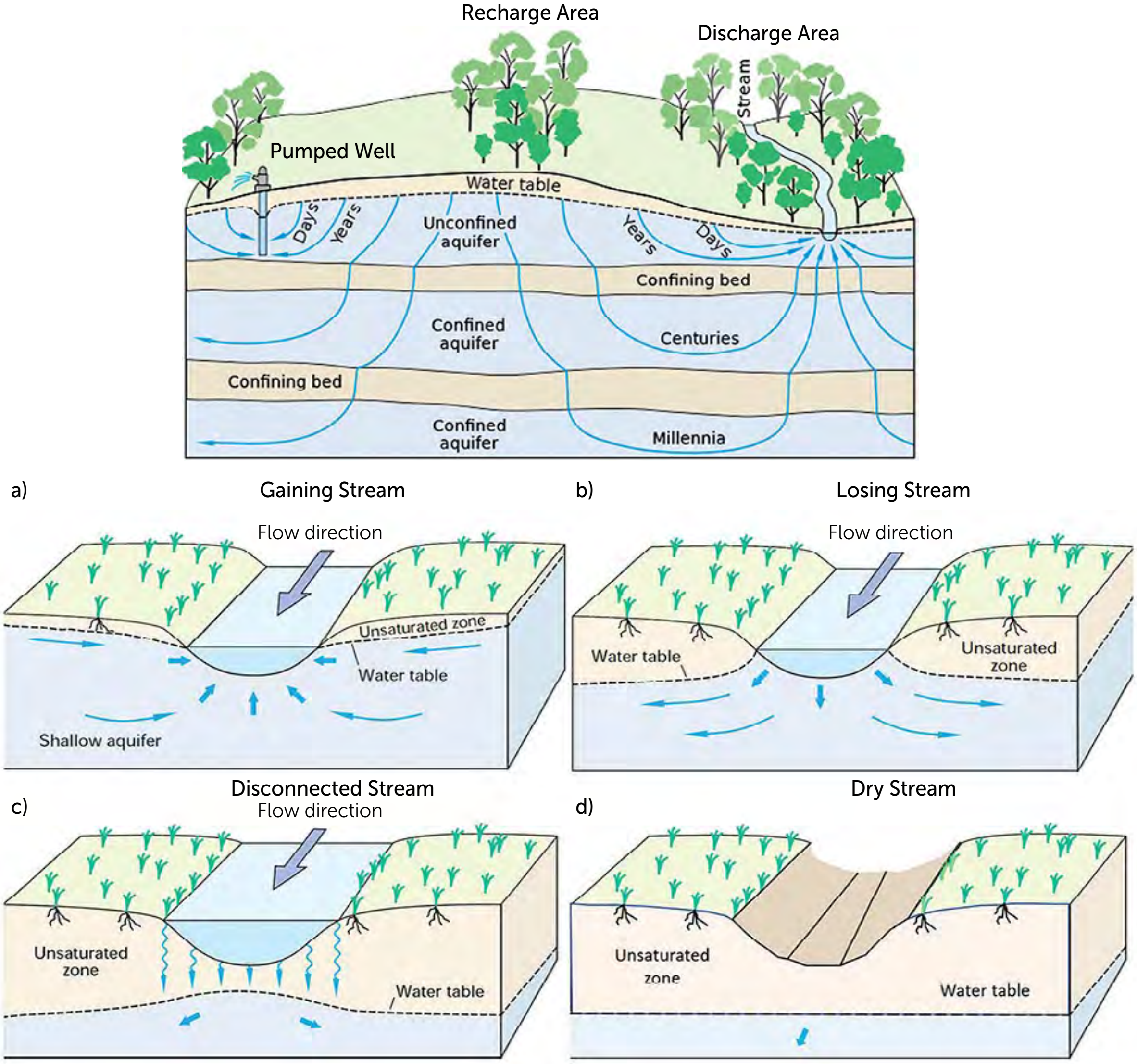

Figure 8. Top: Groundwater flow patterns. Source: (Winter et al., 1998). Bottom, a-d: Groundwater–surface water linkages. Source: (Poeter et al., 2020).

high seasonality in precipitation and river discharge often causes these interactions to reverse intra-annually.

Groundwater management approaches have evolved significantly to capture adequately the ecological complexities and increasing societal and climatic pressures on groundwater resources. Both (Gleeson et al., 2020) and (Elshall et al., 2020) have recently reviewed groundwater management approaches and put forward suggestions for sustainable groundwater management in the Anthropocene. In short, the estimation of safe abstraction rates has been replaced by an adaptive learning approach which aims collaboratively to steer groundwater use in line with ecological and environmental requirements, human needs, the impact of climate change, and society's adaptive capacity (Figure 9). This is not to say that the estimation of groundwater recharge, safe yield (or abstraction) and ecological flow requirements are not important, but rather that these are guardrails for helping communities and societies in adopting ecosystem-based approaches which ensure productive and inclusive water use within ecologically safe limits. A major reason for this shift in thinking is that the response of groundwater resources to climate change or increased pumping is often hard to predict, as both recharge and discharge patterns might change with increased pumping, and aquifer heterogeneity is often not adequately captured in the simplified models, especially at the local scale.

Gleeson et al., 2020 suggest that groundwater sustainability requires dynamic aquifer fluctuations to stay within acceptable limits (see blue band in Figure 10) and avoid groundwater use which leads to moving temporarily (yellow line) or permanently (red line) beyond these limits. Due to the context specificity of groundwater management, sustainability indicators need to be locally negotiated to fit specific ecological and social needs and circumstances. Estimates of groundwater recharge, safe abstraction limits and ecological flows are important tools to ground these negotiations in facts and evidence, while a better understanding of local hydrogeology allows more granular guidance of groundwater management. However, management decisions and plans must ultimately be based on negotiated assumptions about how to define sustainability and rely on adequate and publicly available monitoring data.

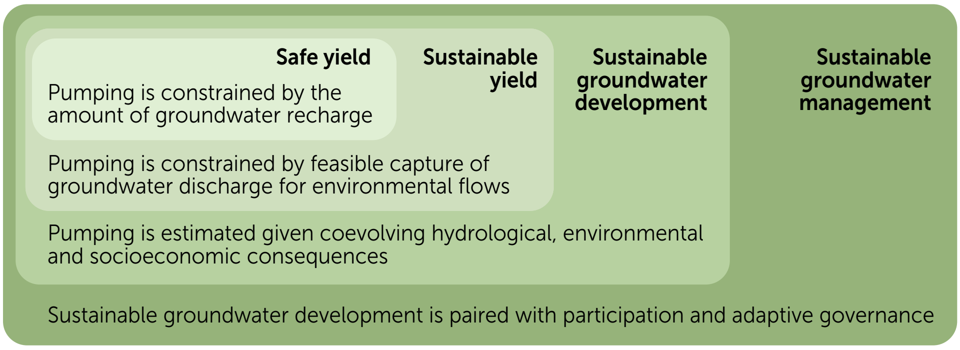

Figure 9. Evolution of groundwater management approaches. Source: Elshall et al., 2020.

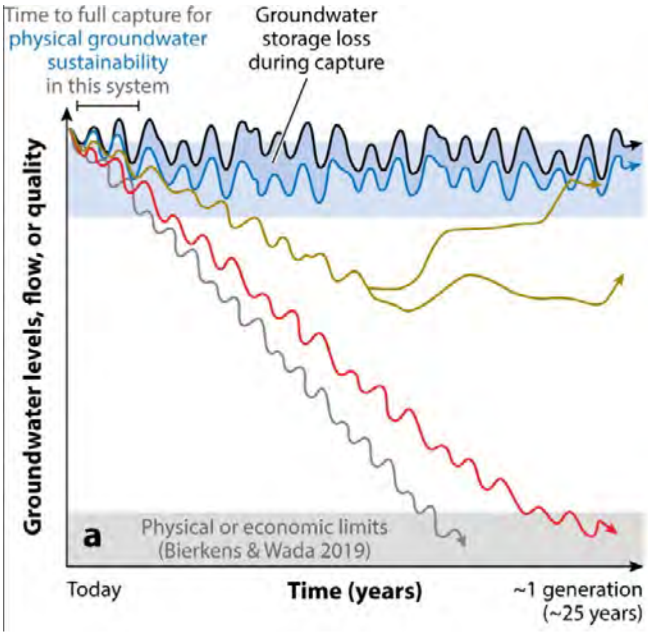

Figure 10. Conceptual outline of (un)sustainable groundwater management in the Anthropocene. Source: Gleeson et al., 2020.

6.2. Groundwater resources and management in Nepal

Groundwater resources in Nepal have been widely explored since the 1970s, and groundwater use – both rural and urban – has skyrocketed since the early 2000s (Mukherjee, 2018). Subsequently, groundwater depletion in Kathmandu Valley, the drying of springs in the Mid-Hills, and localized depletion in the Tarai have resulted in water shortages leading to heightened media attention to the vulnerability of the groundwater resource and the need for sustainable management. Initial work on revitalizing springs in the Mid-Hills outlines potential solutions for sustainable groundwater management (see, among others, Matheswaran et al., 2019; Shrestha et al., 2017) and groundwater data in Kathmandu has been found to be adequate, but management is uncoordinated and lacks a legal and economic framework (Pandey et al., 2011; Shrestha et al., 2018). Groundwater resources and their management in the Tarai – Nepal's breadbasket – have received less attention.

In the Tarai, hydrogeological studies conducted in the 1970s to the 2000s provide a good overview of the hydrogeological setup (GDC, 1994; UNDP, 1992). With CSISA support, the GWRDB – the government agency that oversaw these studies (for reference to groundwater mandates, see Section 3) – is digitizing its library so that these valuable reports are more readily available. For example, Figure 11 shows that the Tarai's aquifers consist of multi-layered sand bodies that have been deposited by both the large and ephemeral rivers of Nepal across geological timescales. From the knowledge of this formation process and existing hydrogeological studies, it is generally assumed that:

(i) aquifers are more productive the closer they are in latitude to major river systems (because rivers flow north to south; see Figure 11, bottom, a)

(ii) aquifers have a strong degree of longitudinal (north–south) consistency (Figure 11, bottom, c, d)

(iii) latitudinally aquifers are much more variable, with lower connectivity at the landscape level (Figure 4, bottom).

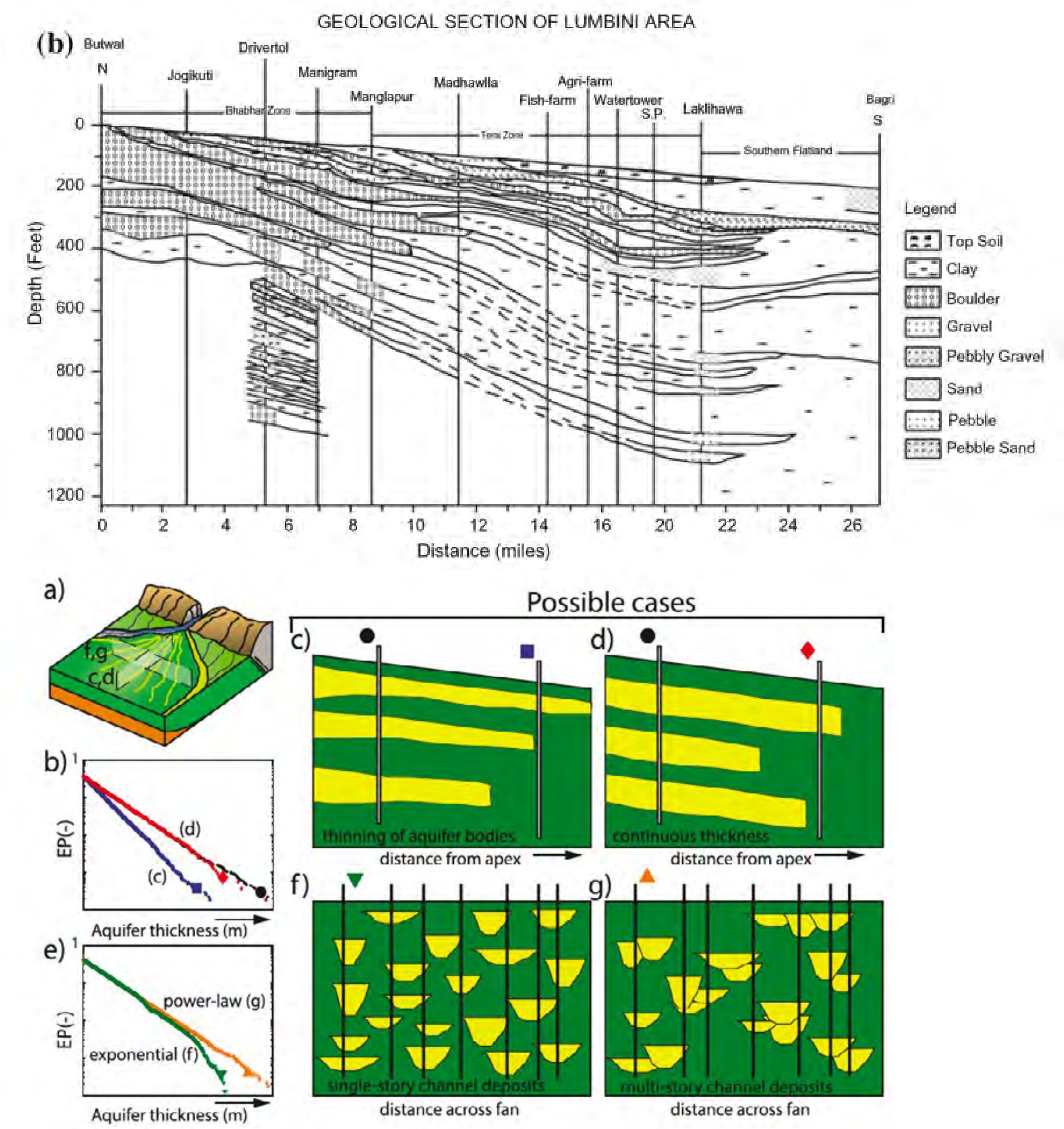

Figure 11. Aquifer characteristics in Nepal and the Indo-Gangetic Plains. Top: (GDC, 1994). Bottom: (van Dijk et al., 2016).

These studies also show that the permeability of the aquifers is generally higher near the Himalayan foothills (Churia range) in an area called Bharbar zone and that groundwater recharge is estimated to be higher in this region. The high permeability of the Bharbar zone has led to a popular belief that most groundwater is recharged here. However, this is not verified, and several GWRDB reports estimate that most recharge derives from percolation in the Tarai plains, which have a lower permeability but a much larger surface area than the Bharbar zone (UNDP, 1992); detailed isotopic studies of groundwater flows here have not been conducted. The large proportion of groundwater recharge in the Tarai plains also suggests that canal irrigation schemes are major sources of groundwater recharge through seepage losses and continuously flooded rice cultivation. Relatively less is known about recharge processes from the Churia range, which are suspected to contribute to regional recharge to deeper, more regional aquifers – again, insufficient data exists to confirm this. Lastly, the GWRDB-curated reports also estimate that the groundwater flow to India is very small (~3%–10%) but point out that better data on aquifer properties are required to make an accurate estimate (UNDP, 1992).

The rather dated aquifer studies of Nepal's Tarai align well with recent research conducted into similar aquifer systems in Northwestern India, which found the aquifers largely comprise old, buried river channels with little connectivity (van Dijk et al., 2016) and that groundwater recharge near canals and surface water bodies is significantly higher than areas without surface water irrigation. This indicates that most shallow aquifers are largely local aquifer systems, and sustainable management thus depends predominantly on local abstraction and recharge patterns for wells shallower than 80 m below ground level (Joshi et al., 2018). However, more data are required to confirm these estimates in Nepal.

6.3. Ways forward

More detailed studies and better groundwater monitoring and governance are required to allow for sustainable groundwater management in Nepal's Tarai – where agricultural production and crucial ecosystems depend on it. Although historically there is little evidence of groundwater depletion in the Tarai (Figure 12), local reports of wells running dry should sound alarm bells for both agricultural planning and ecosystem conservation. At least 50% of farmers in the Tarai rely on groundwater for irrigating their crops and buffering against dry spells (Urfels et al., 2020), while the key protected ecosystems of the Tarai Arc Landscape depend on groundwater for conserving wildlife including tigers, the sarus crane, the one-horned rhinoceros, the wild Asian elephant and the South Asian River dolphin (MoFSC, 2015) (Figure 13). At the same time, the Churia range is experiencing increasing levels of deforestation, sand mining and other pressures that might impact the Tarai's groundwater resource as well as key local and regional ecosystems (GCF, 2019). Expanding and improving the groundwater monitoring system that has been piloted in this study and is currently being transferred to government servers (www.gw-nepal.com) can be the first step – however, this requires adequate policy processes and resources dedicated to improving the system and how it translates information into action. Key management objectives for sustainable groundwater management in Nepal's Tarai comprise advancing the knowledge base to better understand aquifer characteristics and developing management modalities, where monitoring programs enable evidence-based coordination mechanisms which support governments and local communities to build a nature-positive and resilient food system.

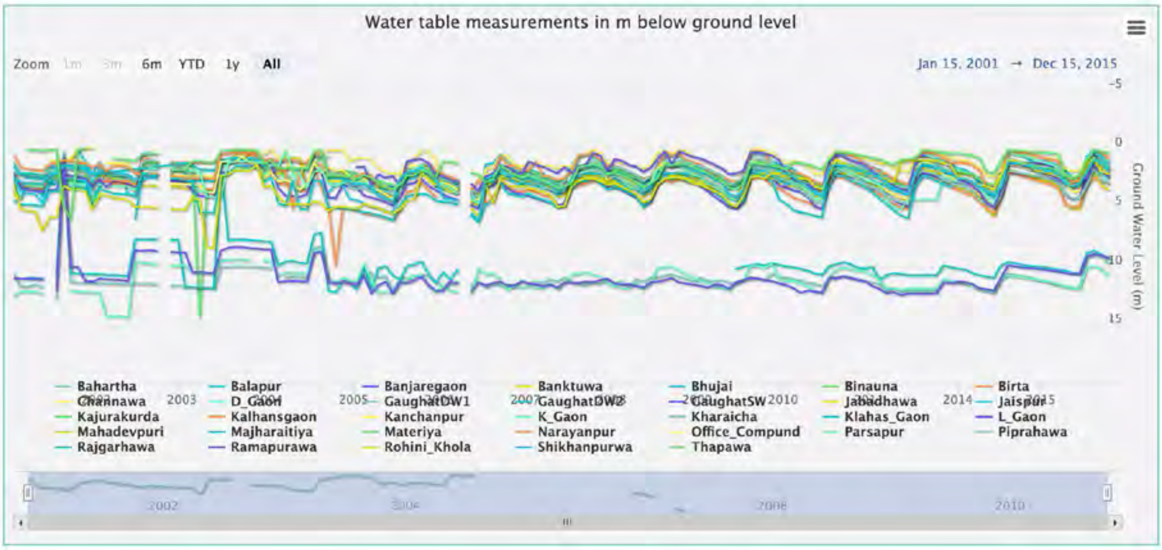

Figure 12. Historical groundwater levels in Banke district, Western Nepal. Source: GWRDB/CSISA, www.gw-nepal.com.

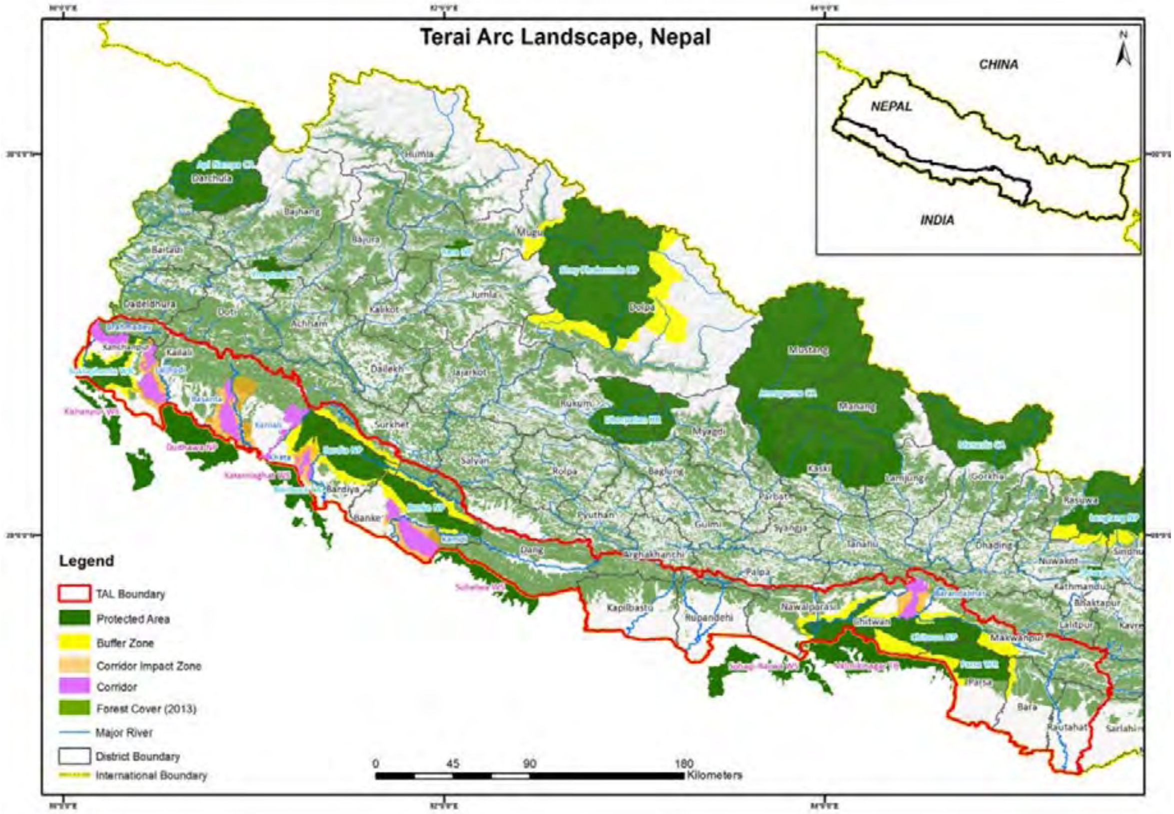

Figure 13. Map of protected areas in the Tarai Arc Landscape conservation strategy for Nepal. Source: (MoFSC, 2015).

7. Applying this framework across Nepal

This section outlines the potential of the sustainable irrigation scaling framework presented in this report to be applied to other regions of Nepal. This report was developed specifically within the context of Nepal's USAID FtF Zone of Influence, which covers most parts of Lumbini Province, Sudurpashchim Province and Karnali Province in Western Nepal. Eastern regions of Nepal have varying socio-economic, agro-ecological and water system-related characteristics. For example, the Koshi river is Nepal's biggest river with almost 50% more discharge than the Karnali river (the biggest river in Western Nepal). Similarly, annual rainfall in the East is significantly higher (e.g. East/Biratnagar 1650 mm, West/Tikapur 1350 mm). Socio-economically, the Mid-Hills in the East are also generally more prosperous and less prone to poverty, while the Tarai districts are more homogenous with regard to poverty indicators (NPC, 2021).

Nevertheless, in Eastern Nepal, the same monsoon climate and topographical patterns exist, as well as similar issues around gender and social inclusion, socio-economic development, and challenges in terms of the implementation of federalism. We suggest therefore that the framework can be applied to the Eastern regions of Nepal. At the same time, other modeling studies have developed watershed models for these regions of Nepal (DWRI, 2019; WECS & CSIRO, 2020). Unfortunately, the model data are not openly available, and it is suggested that future assessments publish their models and data so that they can be reproduced by other researchers in future studies.

In addition, this report focuses largely on the Tarai districts (where the majority of Nepal's agricultural land and population are located), mainly because there are many fewer data resources on water and agriculture in the Mid-Hill districts compared to the Tarai. Robust assessments of the potential for irrigation scaling in the Mid-Hills thus require especially strong data collection efforts. Some of these can be achieved by extending existing data collection systems (such as production surveys and groundwater monitoring) to districts in the Mid-Hills. However, the larger transport and logistics costs of operating in the Mid-Hills further increases the transactional cost on investments here. In broad strokes, the findings of the report are also true for the Mid-Hills, albeit probably more difficult to implement on a large scale. Furthermore, the Mid-Hills have some additional opportunities pertinent to the specific challenges and opportunities of mountain agriculture. These include (a) conservation efforts on sloping lands, (b) revitalization of springs, (c) developing niche mountain products for export, and (d) tourism. These might have additional positive impact on water availability downstream but are currently difficult to quantify robustly, due to lack of sufficient data resources.

8. Recommendations for investment in sustainable and inclusive farmer-led irrigation development

This section summarizes the key recommendations based on the insights presented in the previous sections of this report. Figure 14 provides an overview of the main messages. The recommendations are structured according to the overall framework elements and include an additional section on GESI-related recommendations that cut across all other elements. In addition to GESI, climate change and the impact of COVID-19 receive pronounced attention and are woven throughout the recommendations. Each section starts with an overall key recommendation statement followed by a list of more specific and actionable recommendation items.

Sustainable and inclusive irrigation development requires integrating irrigation policies and practices with broader ecological and societal transformation and change processes. This means that no one solution is generally applicable. The commitments of development partners to support the Government of Nepal pledging USD6.6 billion under the Green Recovery Plan could be an entry point for scaling inclusive and sustainable farmer-led irrigation development.

Overall, our analysis suggests that policymakers and development practitioners should follow the following three guiding principles for ensuring that sustainable and inclusive irrigation development in Western Nepal is context-specific and demand-driven:

1. Prioritize adaptive technology and water management practices that respond to local resource constraints and equity considerations
2. Build robust data and information systems to allow adaptive planning, prepare for climate change impacts, and support digital agriculture and targeted farm advisories
3. Expand and upgrade irrigation and agricultural value chains to ensure access to water, returns on investments, and the creation of better more inclusive jobs

The following graphic summarizes recommendations for each enabler of this framework and provides an orientation for structuring and guiding investments across various sectors. The sections below provide more detailed and specific recommendations for each enabler. For more context on each enabler, please refer to the relevant sections of the framework.

Sustainable and inclusive irrigation development

Policy and governance

Establish clear and inclusive multi-stakeholder coordination mechanism, institutional capacities, and evidence-based policies across levels of government, line ministries, and the private sector in line with constitutional principles.

Agricultural and irrigation value chains

Strengthen upstream and downstream industries and their linkages with strong GESI provisions and targeted demand-driven upgrading based on improved market intelligence and transdisciplinary understanding of key bottlenecks.

Water resources assessments

Strenghten data assests with open access policies, and institutionalize regular monitoring of water quantity and quality to build capacity for sustainable and adaptive management and conservation as water demand and climate change impacts increase.

Knowledge for agricultural water management

Leverage big data, digital transformation, and climate services to provide GESI-responsive, targeted, and bundled advisories and trainings on irrigation management, agronomic practices, and commercial aspects of farm management.

Infrastructure operation and management

Develop institutional capcity across all levels for GESI-responsive and sustainable management and development of smallholder and farmer-led irrigation infrastructure including groundwater and surface water systems.

Gender Equality and Social Inclusion

Integrate GESI provisions upfront across all sectors, programs, and policies to support sustained access and use of irrigation-led upgrading opportunities across value chains for climate-resilient and equitable food system transformation.

Gender Equality and Social Inclusion (GESI)

Climate Change

Capacity Building and Digitalisation

Local Empowerment

Figure 14. Overview of key recommendations with specific mention of issues that cut across all recommendation domains.

8.1. Policy and governance

1. Integrate constitutional GESI principles into institutional guidelines and policies.
2. Build coordination mechanisms for cross-regional and cross sectoral knowledge sharing water and agricultural development policies and interventions .
3. Build human capacity for sustainable water management in the bureaucracy.
4. Strengthen research and innovation networks with transparent and open data stewardship .
5. Build public-private partnerships to develop dynamic private sector capacities for timely and high-quality provisions of agricultural and irrigation goods and services .

8.2. Agricultural value and irrigation supply chains

1. Focus irrigation expansion on areas where value chains are relatively well-developed and align irrigation investments with strengthening of the agricultural inputs sector where these are weak.
2. Closely work with, listen and respond to cooperatives and private sector needs .
3. Generate inclusive farm systems and jobs through incremental upgrading of value chains.
4. Partner with cooperatives to overcome collective action issues in irrigation development.

8.3. Water resources assessments

1. Consolidate open and transparent data assets and information systems on water resources, the projected impact of climate change, and water use.
2. Strengthen groundwater monitoring and regulation to ensure sustainable resource use.
3. Build a strong science–policy interface for translating data into actionable and context-specific information.
4. Aim to conserve water at source and improve productivity downstream.

8.4. Knowledge and capacity for agricultural water management

1. Raise farmer's agronomic capacities along with investments in irrigation.
2. Invest in translating big data resources into specific recommendations such as expected payoffs for increasing irrigation levels and actionable information products that can be used by farmers, extension agents and decision-makers.
3. Integrate climate services into agronomic advisory systems' this can have a greater chance of decreasing farmers' climate risks and encourage farmers' investments in improved agronomic practices.
4. Mainstream GESI provisions into agronomic and irrigation advisory systems; this is indispensable for reaching many farmers and achieving transformative change.

8.5. Sustainable and inclusive operation and management of irrigation infrastructure

1. Existing canal irrigation schemes require improved service and user-oriented management practices through institutional support and capacity development to deliver on their intended mandates.
2. Benchmarking of and capacity building in GESI-sensitive small scale irrigation systems is required to guide the private and public sector towards innovation and capacity building where it is most needed.
3. Institutional capacity can be further developed by creating an active network that documents, disseminates, and celebrates promising cases of inclusive and sustainable small-scale/farmer-led irrigation approaches,
4. Building capacity for coordinating conflicts and sharing good water management practices amongst water users.

8.6. Gender equality and social inclusion (GESI)

1. GESI-responsive programming is required across all sustainable irrigation scaling activities to reach their intended potential and ensure that all voices a heard and accounted for.
2. Women groups and leaders should be proactively targeted through coordination mechanisms and dedicated budgets to assist in reaching their aspirations.
3. Transdisciplinary research to better understand the opportunities and bottlenecks.

References

Acharya, K. P. (2021). Sarkarkai kamjori bho: Aba anusandhan thalau [Translation: Weakness of the government: Let us start research]. *Sarkarkai Kamjori Bho: Aba Anusandhan Thalau [Translation: Weakness of the Government: Let Us Start Research]*. https://www.onlinekhabar.com/2021/09/1017637

Adhikari, B., Verhoeven, R., & Troch, P. (2009). Water rights of the head reach farmers in view of a water supply scenario at the extension area of the Babai Irrigation Project, Nepal. *Physics and Chemistry of the Earth, 34(1-2),* 99–106.

Bastakoti, R. C., Bharati, L., Bhattarai, U., & Wahid, S. M. (2017). Agriculture under changing climate conditions and adaptation options in the Koshi Basin. *Climate and Development, 9*(7), 634–648. https://doi.org/10.1080/17565529.2016.1223594

Bhandari, G. (2013). Assessment of Climate Change Impacts and Adaptation Measures in the Kapilbastu District of Nepal. *Applied Ecology and Environmental Sciences, 1*(5), 75–83. https://doi.org/10.12691/aees-1-5-2

Bhattarai, M. (2008). *Socioeconomic Impacts of Low-Cost Tank with Drip Irrigation for Vegetable Production: A Community-scale Case Study in Nepal.* 1.

Bista, I. (2019). *SMEs Financing in Nepal: Five key findings of the report.*

Bolwig, S., Ponte, S., Du Toit, A., Riisgaard, L., Halberg, N., & Danish Institute for International Studies. (2008). *Integrating poverty, gender and environmental concerns into value chain analysis: A conceptual framework and lessons for action research.* DIIS.

Brouwer, C., Prins, K., & Heibloem, M. (1989). *"Irrigation Water Management: Irrigation Scheduling," Training Manual No. 4.* Food and Agriculture Organization of the United Nations.

Brown, P. R., Anwar, M., Hossain, Md. S., Islam, R., Siddquie, Md. N.-E.-A., Rashid, Md. M., Datt, R., Kumar, R., Kumar, S., Pradhan, K., Das, K. K., Dhar, T., Bhattacharya, P. M., Sapkota, B., Thapa Magar, D. B., Adhikari, S. P., Rola-Rubzen, M. F., Murray-Prior, R., Cummins, J., … Tiwari, T. P. (2021). Application of innovation platforms to catalyse adoption of conservation agriculture practices in South Asia. *International Journal of Agricultural Sustainability,* 1–24. https://doi.org/10.1080/14735903.2021.1945853

CAMRIS. (2020). *USAID/Nepal Hamro Samman Activity Mid-term Performance Evaluation Report*. CAMRIS International. https://pdf.usaid.gov/pdf_docs/PA00X2HB.pdf

CBS. (2013). *National Sample Census of Agriculture, Nepal, 2011/201.* Central Bureau of Statistics (CBS), Government of Nepal.

Danert, K. (2015). Manual drilling compendium. *RWSN Publication, 2.*

Danert, K., Adekile, D., & Canuto, J. G. (2020). Striving for Borehole Drilling Professionalism in Africa: A Review of a 16-Year Initiative through the Rural Water Supply Network from 2004 to 2020. *Water*, 12(12), 3305. https://doi.org/10.3390/w12123305

Doorenbos, J., & Pruitt, W. O. (1977). *Guidelines for predicting crop water requirements (Rev).* Food and Agriculture Organization of the United Nations.

DRCN. (2020). *The Interrelationship between Three Levels of Governments in Nepal's Federal Structure.* Democracy Resource Center Nepal (DRCN).

DWRI. (2019). *Irrigation Master Plan 2019* [Final Report]. Department of Water Resources and Irrigation, Ministry of Energy, Water Resources, and Irrigation, Government of Nepal.

EU. (2020). *Government of Nepal – International Development Partners Joint Statement on Green Recovery in Nepal* [Text]. EEAS - European External Action Service - European Commission. https://eeas.europa.eu/delegations/nepal/90497/government-nepal-%E2%80%93-international-development-partners-joint-statement-green-recovery-nepal_en

FAO. (2019). *Country gender assessment of agriculture and the rural sector in Nepal.* Food and Agriculture Organization of the United Nations. Food and Agriculture Organization of the United Nations

FMIST. (2020). *Feedbacks of stakeholders on the draft water resources bill submitted to the Department of Water Resources and Irrigation- A report based on the webinar organized for stakeholders consultation on the draft WR bill on 14 October 2020.* Farmer Managed Irrigation System Promotion Trust (FMIST).

Foster, T., Adhikari, R., Adhikari, S., Justice, S., Tiwari, B., Urfels, A., & Krupnik, T. J. (2021). Improving pumpset selection to support intensification of groundwater irrigation in the Eastern Indo-Gangetic Plains. *Agricultural Water Management, 256*, 107070. https://doi.org/10.1016/j.agwat.2021.107070

Foster, T., Adhikari, R., Urfels, A., Adhikari, S., & Krupnik, T. J. (2019). *Costs of diesel pump irrigation systems in the Eastern IndoGangetic Plains: What options exist for efficiency gains?* CIMMYT International Maize and Wheat Improvement Center.

Foster, T., & Urfels, A. (2020a). *Reducing Poverty in South Asia Through Accelerating Irrigation Intensification.* https://www.agrilinks.org/post/reducing-poverty-south-asia-through-accelerating-irrigation-intensification.

Foster, T., & Urfels, A. (2020b). *Reducing Poverty in South Asia Through Accelerating Irrigation Intensification.* https://www.agrilinks.org/post/reducing-poverty-south-asia-through-accelerating-irrigation-intensification.

Gartaula, H. N., Niehof, A., & Visser, L. (2010). Feminisation of Agriculture as an Effect of Male Out-migration: Unexpected Outcomes from Jhapa District, Eastern Nepal. *The International Journal of Interdisciplinary Social Sciences: Annual Review, 5*(2), 565–578. https://doi.org/10.18848/1833-1882/cgp/v05i02/51588

Giri, A. (2019). Nepal needs much work before using Chinese sea and land ports. *The Kathmandu Post.* https://kathmandupost.com/national/2019/05/07/nepal-needs-much-work-before-using-chinese-sea-and-land-ports

Giri, A., & Khanal, R. (2019). Only five trucks have crossed the Tatopani border since its reopening. *The Kathmandu Post.* https://kathmandupost.com/national/2019/06/28/only-five-trucks-have-crossed-the-tatopani-border-since-its-reopening

GoN. (2019). *National Climate Change Policy, 2076*. Office of the Prime Minister and Council of Ministers (OPMCM), Government of Nepal.

Gurung, D. B., Kc, D. B., Ferrara, G. O., Gadal, N., Pokhrel, S., Bhandari, D. R., Koirala, B., Bhandari, B. R., & Tripathi, M. (2011). Maize value chains in Nepal. *Addressing Climate Change Effects and Meeting Maize Demand for Asia, 11.*

Gyawali, R. (2009). *Factors and impact of participation on the operation and maintenance of an irrigation system in Nepal: A case study of the babai irrigation project.* AIT.

Havana, O. (2015). Fuel crisis grips Nepal as border crossings close. *Aljazeera.* https://www.aljazeera.com/gallery/2015/9/29/fuel-crisis-grips-nepal-as-border-crossings-close

Honsberger, A. L. (2015). *Professionals in their field: Women vegetable farmers in Nepal.* The University of Guelph.

Joshi, A. (2018). Women in agriculture. *The Kathmandu Post.* https://kathmandupost.com/opinion/2018/08/02/women-in-agriculture.

Khadka, M., Bhatta, A., Uprety, L., Shrestha, S., Rajauria, A., Dhungana, S., & Shrestha, N. (2021). *Policies, plans, strategies, and priorities of the Government of Nepal on Water-Energy-Food-Environment (WEFE) nexus sectors in Federal Nepal.* IWMI- Nepal.

Khadka, M., Joshi, D., Uprety, L., Shrestha, G., & Suhardiman, D. (N.A.). Gender and socially inclusive WASH under federalism in Nepal: Transformative approaches and pathways for moving beyond 'engineering fixes'. *A Manuscript Prepared for Submitting to a Peer Reviewed International Journal Article.*

Khadka, M., Uprety, L., Shrestha, G., Minh, T. T., Nepal, S., Raut, M., Dhungana, S., Shahrin, S., Krupnik, T. J., & Schmitter, P. (2021). *Understanding barriers and opportunities for scaling sustainable and inclusive farmer-led irrigation development in Nepal* (p. 96). The Cereal Systems Initiative for South Asia (CSISA).

Khadka, M., Uprety, L., Shrestha, G., Mukherji, A., & Mitra, A. (2021). *Do Water, Energy and Food Nexus Policies Enable Gender Transformative Changes? Evidence from Bangladesh and Nepal.* IWMI- Nepal.

Khanal, N. R., Nepal, P., Zhang, Y., Nepal, G., Paudel, B., Liu, L., & Rai, R. (2020a). Policy provisions for agricultural development in Nepal: *A review. Journal of Cleaner Production, 261,* 121241. https://doi.org/10.1016/j.jclepro.2020.121241

Khanal, N. R., Nepal, P., Zhang, Y., Nepal, G., Paudel, B., Liu, L., & Rai, R. (2020b). Policy provisions for agricultural development in Nepal: *A review. Journal of Cleaner Production, 261,* 121241. https://doi.org/10.1016/j.jclepro.2020.121241

Ladha, J. K., Singh, Y., Erenstein, O., Hardy, B., & International Rice Research Institute (Eds.). (2009). *Integrated crop and resource management in the rice-wheat system of South Asia.* International Rice Research Institute.

Lefore, N., Giordano, M., Ringler, C., & Barron, J. (2019). *Sustainable and Equitable Growth in Farmer-led Irrigation in Sub-Saharan Africa: What Will it Take?* 12(1), 13.

LTS International. (2017). *Sector Analysis Studies for the Commercial Agriculture for Smallholders and Agribusiness Programme. Nepal: Country Value Chain and Market Analysis Report* [Final Report].

Maharjan, A., Bauer, S., & Knerr, B. (2012). Do Rural Women Who Stay Behind Benefit from Male Out-migration? A Case Study in the Hills of Nepal. *Gender, Technology and Development, 16*(1), 95–123. https://doi.org/10.1177/097185241101600105

Manandhar, G. B., Adhikary, S. K., & Sah, G. (2009). Sustainable agricultural practices and technologies in Nepal. *Sustainable Agriculture,* 10.

Mandal, S. N., Regmi, A. P., Ladha, J. K., & Tuong, T. P. (2009). Crop establishment, tillage, and water management effects on crop and water productivity in the rice-wheat rotation in Nepal. In *Integrated crop and resource management in the rice-wheat system of South Asia* (pp. 239–259). International Rice Research Institute.

Marhatta, S., Acharya, R., & Joshi, P. P. (2018). Simulation of growth and yield of rice and wheat varieties under varied agronomic management and changing climatic scenario under subtropical condition of Nepal. *Journal of Agriculture and Forestry University, 2*, 141–156.

Meinzen-Dick, R. S., Pradhan, P., & Zhang, W. (2021). *Migration and gender dynamics of irrigation governance in Nepal* (0 ed.). International Food Policy Research Institute. https://doi.org/10.2499/p15738coll2.134815

Minh, T. T., Zwart, S., Appoh, R., & Schmitter, P. (2021). *Analyzing the enabling environment to enhance the scaling of irrigation and water management technologies: A tool for implementers.* International Water Management Institute (IWMI). https://doi.org/10.5337/2021.201

Ministry of Labor, Employment and Social Security. (2020). *Nepal Labor Migration Report 2020*. Ministry of Labor, Employment and Social Security. https://moless.gov.np/wp-content/uploads/2020/03/Migration-Report-2020-English.pdf

Mishra, Y., Babel, M. S., Nakamura, T., & Mishra, B. (2021). Impacts of Climate Change on Irrigation Water Management in the Babai River Basin, Nepal. *Hydrology, 8*(2), 85. https://doi.org/10.3390/hydrology8020085

MOAD. (2016). *Agriculture Development Strategy, 2015-2035. Part I.* Ministry of Agricultural Development (MoAD).

MoEWRI. (2020). *National Water Resources Policy: 2077.* Ministry of Energy, Water Resources and Irrigation, Government of Nepal.

MOFE. (2020). *The Second Nationally Determined Contribution (NDC).* Ministry of Forests and Environment.

myRepublica. (2021). *New budget allocates Rs 45.09 billion for agriculture.* https://myrepublica.nagariknetwork.com/news/new-budget-allocates-rs-45-09-billion-for-agriculture/

Nepal Rastra Bank. (2014). *Agricultural Credit and Its Impact on Farm Productivity: A Case Study of Kailali District.* Nepal Rastra Bank, Banking Development and Research Unit.

Nepal, S., Neupane, N., Belbase, D., Pandey, V. P., & Mukherji, A. (2019). Achieving water security in Nepal through unravelling the water-energy-agriculture nexus. *International Journal of Water Resources Development, 37*(1), 67–93. https://doi.org/10.1080/07900627.2019.1694867

NLC. (2017). *Inter-Governmental Fiscal Management Act, 2074 BS.* Nepal Law Commission (NLC), Government of Nepal.

NPC. (2019). *The 15th Plan, 2019-2023 and Approach Paper.* National Planning Commission (NPC), Government of Nepal.

NPC. (2020). *The 15th Plan, 2019-2023- Unofficial Translation.* National Planning Commission (NPC), Government of Nepal.

NPC. (2021). *Nepal Multidimensional Poverty Index Analysis Towards Action.* National Planning Commission (NPC), Government of Nepal.

Ortiz-Monasterio R., J. I., Dhillon, S. S., & Fischer, R. A. (1994). Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. *Field Crops Research, 37*(3), 169–184. https://doi.org/10.1016/0378-4290(94)90096-5

Pakhtigian, E. L., Jeuland, M., Dhaubanjar, S., & Pandey, V. P. (2020). Balancing intersectoral demands in basin-scale planning: The case of Nepal's western river basins. *Water Resources and Economics, 30*, 100152. https://doi.org/10.1016/j.wre.2019.100152

Pandey, J. (2018). Youth Sensitivity of Labor Laws and Policies. In Youth Employment in Nepal. World bank.

Pandey, V. P., Ray, A., Khadka, M., Urfels, A., & Krupnik, T. J. (2021). *Towards Conjunctive Use of Surface Water and Groundwater Resources as a Response to Water Access Challenges in the* (p. 115). The Cereal Systems Initiative for South Asia (CSISA).

Panta, H. K. (2018). Supply Chain of Subsidized Chemical Fertilizers in Nepal. *Journal of the Institute of Agriculture and Animal Science, 35*(1), 9–20. https://doi.org/10.3126/jiaas.v35i1.22509

Pathak, D. (2018). Status of groundwater exploitation and investigation in Terai and Inner Teri region of Nepal. *Bulletin of Nepal Hydrogeological Association, 3*, 77–83.

Pokharel, N., Ghimire, A., Thapa, B. S., & Thapa, B. (2020). Opportunity for research and manufacturing of pump in Nepal. *Journal of Physics: Conference Series, 1608*(1), 012018. https://doi.org/10.1088/1742-6596/1608/1/012018

Poudel, D. P., & Khatri, D. (2019). *Natural Resources Sharing in Federalizing Nepal: Issues and Contestations.* SouthAsia Institute of Advanced Studies (SIAS).

Poudel, G., & Pokharel, B. (2018). Women's Empowerment Through Small Farmers' Cooperatives: A Case Study from Eastern Nepal. *Journal of Advanced Academic Research, 4*(2), 68–78. https://doi.org/10.3126/jaar.v4i2.19536

Pradhan, P. (2000). *Farmer Managed Irrigation Systems in Nepal at the Crossroad*. http://dlc.dlib.indiana.edu/dlc/bitstream/handle/10535/331/pradhanp041500.pdf?sequence=#:~:text=In%20Nepal%2C%20Farmer%20Managed%20Irrigation,still%20active%20institutions%20in%20Nepa

Pradhan, P., & Belbase, M. (2018). Institutional Reforms in Irrigation Sector for Sustainable Agriculture Water Management including Water Users Associations in Nepal. *Hydro Nepal: Journal of Water, Energy and Environment, 23*, 58–70. https://doi.org/10.3126/hn.v23i0.20827

Pradhan, P., Parjuli, U. N., & Khanal, R. C. (2017). *Framework for effectiveness and resilience of small- and medium-scale irrigation systems in Nepal.* UK Department for Intentational Development.

Prasain, S., & Giri, A. (2015). Nepal's fertiliser conundrum–governments ponder over it every paddy season and then forget after harvest. *The Kathmandu Post.* https://tkpo.st/2YZ72dl

Rola-Rubzen, M. F., Paris, T., Hawkins, J., & Sapkota, B. (2020). Improving Gender Participation in Agricultural Technology Adoption in Asia: From Rhetoric to Practical Action. *Applied Economic Perspectives and Policy, 42*(1), 113–125. https://doi.org/10.1002/aepp.13011

Saini, S. (2020). *Nepal's predicament: Delays in fertilizer imports and its implications on upcoming paddy season.* International Food Policy Research Institute.

Schmidt, E., Sugden, F., Scobie, M., Mainuddin, M., Mishra, S., Thapa, B., Bastakoti, R. C., & Da Silva, S. (2019). *Final report—Improving water use for dry season agriculture by marginal and tenant farmers in the Eastern Gangetic Plains* (p. 116) [Final Report]. ACIAR.

Sharma, S. P., & Adhikary, S. (2020). *Securing Safe Water and Sanitation Services in Nepal Search for a Breakthrough.* Nepal Water Conservation Foundation.

Shrestha, G., & Clement, F. (2019). Unravelling gendered practices in the public water sector in Nepal. *Water Policy, 21*(5), 1017–1033. https://doi.org/10.2166/wp.2019.238

Shrestha, S., Adhikari, S., Babel, M. S., Perret, S. R., & Dhakal, S. (2015). Evaluation of groundwater-based irrigation systems using a water–energy–food nexus approach: A case study from Southeast Nepal. *Journal of Applied Water Engineering and Research, 3*(2), 53–66. https://doi.org/10.1080/23249676.2014.1001881

Shrestha, S., Chapagain, P. S., & Ghimire, M. (2019). Gender Perspective on Water Use and Management in the Context of Climate Change: A Case Study of Melamchi Watershed Area, Nepal. *SAGE Open, 9*(1), 215824401882307. https://doi.org/10.1177/2158244018823078

Shrestha, S. R., Tripathi, G. N., & Laudari, D. (2018). Groundwater Resources of Nepal: An Overview. In A. Mukherjee (Ed.), *Groundwater of South Asia* (pp. 169–193). Springer Singapore. https://doi.org/10.1007/978-981-10-3889-1_11

Shrestha, S., & Uprety, L. (2021). *Solar irrigation in Nepal: A situation analysis report.* International Water Management Institute (IWMI). https://doi.org/10.5337/2021.218

Stoian, D., Donovan, J., Elias, M., & Blare, T. (2018). Fit for purpose? A review of guides for gender-equitable value chain development. *Development in Practice, 28*(4), 494–509. https://doi.org/10.1080/09614524.2018.1447550

Subedi, R. (2018). *Women farmers' participation in agriculture training: In Kavre district of Nepal* [Larenstein university of applied sciences]. https://edepot.wur.nl/1198

Sugden, F. (2014). *Landlordism, tenants and the groundwater sector: Lessons from Tarai-Madhesh, Nepal.* International Water Management Institute (IWMI). https://doi.org/10.5337/2015.204

Sugden, F., Agarwal, B., Leder, S., Saikia, P., Raut, M., Kumar, A., & Ray, D. (2020). Experiments in farmers' collectives in Eastern India and Nepal: Process, benefits, and challenges. *Journal of Agrarian Change, 21*(1), 90–121. https://doi.org/10.1111/joac.12369

Suhardiman, D., Bastakoti, R. C., Karki, E., & Bharati, L. (2018). The politics of river basin planning and state transformation processes in Nepal. *Geoforum, 96,* 70–76. https://doi.org/10.1016/j.geoforum.2018.07.019

Thapa, G., Kumar, A., & Joshi, P. K. (Eds.). (2019). *Agricultural Transformation in Nepal: Trends, Prospects, and Policy Options.* Springer Singapore. https://doi.org/10.1007/978-981-32-9648-0

Tractebel Engineering GmbH. (2019). *Irrigation Master Plan* [Main Report]. Water Resources Project Preparatory Facility (WRPPF), Department of Water Resources and Irrigation. Ministry of Energy, Water Resources and Irrigation.

Udas, P. B. (2014). *Gendered participation in water management in Nepal: Discourses, policies and practices in the irrigation and drinking water sectors.* Wageningen University and Research.

Udas, P. B., & Zwarteveen, M. Z. (2010). Can water professionals meet gender goals? A case study of the Department of Irrigation in Nepal. *Gender & Development, 18*(1), 87–97. https://doi.org/10.1080/13552071003600075

UN Women. (2017). *Women farmers of Nepal take charge of their lives and livelihoods.* unwomen.org/en/news/stories/2017/2/feature-women-farmers-of-nepal-take-charge-of-their-lives

UN Women. (2020). *Gender Equality and Social Inclusion (GESI) Profile for COVID-19 Responses and Preparedness.* UN Women. https://asiapacific.unwomen.org/sites/default/files/Field%20Office%20ESEAsia/Docs/Publications/2020/05/Nepal%20GESI%20Profile_Updated%208%20May%202020_vr6-b%28004%29.pdf

UNDP. (2020). *Rapid Assessment of Socio Economic Impact of COVID-19 in Nepal.* United Nations Development Program (UNDP).

Urfels, A., McDonald, A. J., Krupnik, T. J., & van Oel, P. R. (2020a). Drivers of groundwater utilization in water-limited rice production systems in Nepal. *Water International, 45*(1), 39–59. https://doi.org/10.1080/02508060.2019.1708172

Urfels, A., McDonald, A. J., Krupnik, T. J., & van Oel, P. R. (2020b). Drivers of groundwater utilization in water-limited rice production systems in Nepal. *Water International, 45*(1), 39–59. https://doi.org/10/gmx3zp

Urfels, A., McDonald, A. J., Krupnik, T. J., & van Oel, P. R. (2020c). Drivers of groundwater utilization in water-limited rice production systems in Nepal. *Water International, 45*(1), 39–59. PubMed. https://doi.org/10.1080/02508060.2019.1708172

Urfels, A., McDonald, A. J., van Halsema, G., Struik, P. C., Kumar, P., Malik, R. K., Poonia, S. P., Balwinder-Singh, Singh, D. K., Singh, M., & Krupnik, T. J. (2021). Social-ecological analysis of timely rice planting in Eastern India. *Agronomy for Sustainable Development, 41*(2), 14. https://doi.org/10/gh5g68

WB. (2021). *Nepal's Journey to Green, Resilient, and Inclusive Development.* https://blogs.worldbank.org/endpovertyinsouthasia/nepals-journey-green-resilient-and-inclusive-development

WECS, & CSIRO. (2020). *State of the Kamala River Basin, Nepal.* WECS and CSIRO.

Yadav, I. C., Dhuldhaj, U. P., Mohan, D., & Singh, S. (2011). Current status of groundwater arsenic and its impacts on health and mitigation measures in the Terai basin of Nepal: An overview. *Environmental Reviews, 19*(NA), 55–67. https://doi.org/10.1139/a11-002

Yadaw, R. (2018). Rice Technological Innovation and Value Chain Development in Nepal: Current Status and Future Directions. In *Rice Technological Innovation and Value Chain Development in South Asia: Current Status and Future Directions.* SAARC Agriculture Centre.

Yoder, R., & Adhikari, D. (2015). *Low-cost Manual Well Drilling: Village Mistris Make Groundwater Accessible for Irrigation.* Sixth Seminar of the Farmer Managed Irrigation Systems (FMIS) Promotion Trust, Kathmandu, Nepal.

Annex I – Research Report

Potential impacts of cropping and management interventions on resilient and sustainable irrigation development in Lumbini and Sudurpashchim provinces of Nepal (Feed the Future Zone of Influence)

The CSISA Nepal Covid-19 Response and Resilience Activity

Work Package II

April 2022

Executive Summary

Agriculture is Nepal's primary economic activity, providing 28% of gross domestic product and employing about 66% of the total population. However, productivity and the level of income obtained from agriculture is very low and about 4.6 million people continue to face food security challenges. The lack of sustainable irrigation facilities is one of the main reasons for low productivity. Although irrigation requires only a small fraction of annual river flows, seasonality challenges surface/groundwater irrigation in the dry season. Despite the availability of irrigation systems, some crops face water stress, especially when smaller and medium-sized rivers are utilized as the main source of water. Moreover, the construction of big irrigation projects is very costly and may not be economical everywhere. Crop productivity and profitability can also be improved with the selection of suitable agricultural management and careful utilization of existing resources in a sustainable manner. The monsoon season crop usually gets enough water from precipitation and requires irrigation only at times during the year of less rainfall or when the monsoon season rainfallit starts late. Groundwater can be preserved for the dry season by extracting it for irrigation only when required – for example, when there are rainfall variabilities such as drought and dry spells, and during periods when rainfall starts or ends late. In this study, modeling techniques were used to evaluate different hypotheses regarding the application of cropping and management interventions, and to suggest suitable interventions for the sustainable use of surface/groundwater extraction and thereby improvement to crop productivity. The report studied a number of scenarios, developed based on stakeholder engagment meetings: closing the yield gap in the rice–wheat system, cultivating vegetables between *kharif* and spring rice, replacing lentil and fallow with irrigated maize, using a triple-cropping instead of a double-cropping system, replacing rainfed *rabi* crops with horticultural crops, and maximizing the groundwater recharge in the Mid-Hills. A summary of key findings on the sustainability of water resources and crop productivity based on the scenario analysis is provided below.

Sustainability of water resources

Surface/groundwater will be sustainable if its flow/storage is retained dynamically for the long-term through inclusive, equitable and long-term management and governance (Gleeson et al., 2020). The scenario of closing the yield gap in the rice–wheat irrigation system through expanding surface and groundwater irrigation was shown to be sustainable in the Mahakali and Karnali watersheds as it did not rely on a single water resource, but instead took 50% of the irrigation requirement from the surface water source and 50% from the groundwater source. Integrated surface/groundwater use such as this can lessen the potential impact of farmers relying on either one or the other. As Karnali and Mahakali are large perennial rivers, the Tarai region of Kanchanpur, Kailali and Bardiya districts has access to irrigation from projects such as the Mahakali, Ranijamara and Rajapur irrigation projects and thus can be supplied with year-round surface irrigation. On the other hand, Babai and West Rapti rivers have a very low flow during pre-monsoon and post-monsoon seasons, and therefore do not have sufficient water to divert water into the canal after leaving 30% of the flow in the river as environmental flow. For this reason, the yield gap-closing scenario may not be sustainable in terms of groundwater resources in the Babai and West Rapti watersheds, as both the supplemental irrigation for the monsoon and irrigation for winter season crops rely on groundwater. The scenario may be sustainable in these watersheds if the cultivated area during the dry season is reduced by 40% and supplementary irrigation is applied in the monsoon season in all suitable areas. However, this is a short-term solution; groundwater sustainability can be achieved through the implementation of sustainable land management practices (for example, composting/mulching, conservation tillage and plantation of cover crops) to reduce evaporation and promote groundwater recharge. Such practices help to enhance groundwater recharge and reduce the risk of groundwater overexploitation over time.

Groundwater irrigation was sustainable for the rice–vegetable–rice system when the dry season crops (vegetable and spring rice) were provided with groundwater irrigation and the monsoon season crop (monsoon rice) received supplementary irrigation from surface water sources. If all the irrigation requirements need to be fulfilled by a groundwater source alone, only 48% to 52% of the total land in the Babai watershed, 63% of the cultivated land in the Mahakali watershed, and 45% to 61% of cultivated land in the Karnali watershed can be provided with groundwater sustainably.

Similarly, as lentil requires less water than maize, the rice–lentil system was sustainable with current water resources, but the rice–irrigated maize system was sustainable only when the dry season crop (maize) was provided with groundwater irrigation and the monsoon season crop (rice) was either provided with surface water irrigation or rainfed. If all the irrigation requirements need to be fulfilled by the groundwater source alone, only 61% to 81% of the total land can be provided with groundwater sustainably.

In the same way, for the rice–mungbean–wheat system, only 27% to 39% of currently cultivated land in the Karnali watershed and 36% to 44% of currently cultivated land in West Rapti watershed can be provided with groundwater sustainably. These suitable croplands could sustainably extract groundwater if dry season crops were provided with groundwater irrigation and supplementary irrigation from surface water sources for the monsoon season crops.

Crop productivity

Average rice and wheat yields may increase by 17% to 80% and 30% to 217%, respectively if irrigation facilities were expanded in suitable areas for irrigation in Nepal. Of the scenarios, the rice–vegetable–rice (rather than rice–wheat) showed the highest increase in production in the current and future climates. For example, in the scenario, the cultivation of rice–vegetable–rice instead of rice–wheat increased total rice equivalent production by 51% in the current term (2000–21), 17% during the near-term future (2021–35) and 34% during the mid-term future (2035–50). Similarly, in the scenario, the cultivation of rice–irrigated maize instead of rice–lentil decreased the total rice equivalent production by 5% in the current term (2000–21), 11% during the near-term future (2021–35) and 18% during the mid-term future (2035–50) because of the price of lentil being higher than corn. In the same way, in the scenario, triple cropping instead of the current rice–wheat increased total rice equivalent production by 130% in the current term (2000–21), 84% during the near-term future (2021–35) and 266% during the mid-term future (2035–50) due to the higher price of mung bean in comparison to rice and wheat. The scenario also showed that cultivating horticulture crops instead of wheat increased the total rice equivalent production by 61% in the current term (2000–21), 65% during the near-term future (2021–35) and 35% during the mid-term future (2035–50) due to the higher price of potato. In general, crop yield and production for winter and spring season crops were low even after sufficient irrigation and fertilizer application due to the short growing period and temperature stress. The cultivation of such crops in dry seasons using irrigation does not therefore seem to be worth it. However, crops with a short growing period (such as lentil) could be suitable for winter, as these have economic and environmental benefits.

Similarly, decreases in crop yield and production during the near- and mid-term future compared to the current period were due to temperature stress. Perhaps during short periods such as the winter and spring seasons, farmers can consider crops which have short growing periods, such as lentil. Lentil generally requires 80 to 110 days to provide yield and in addition to its high economic value, being a legume crop it improve soil fertility.

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1. Introduction

Context of the study

Nepal is among the richest countries in the world in terms of water resources, with 210 km^3 of total renewable freshwater resources per year and 7173 m^3 of freshwater resources per person per year. (World Bank, 2021). Ninety percent of this water comes from a surface water source such as glaciers, rivers, springs and lakes; the remaining comes from a groundwater source (WEPA, 2021). Ninety-eight percent of the water extracted from both surface and groundwater sources is used for irrigation purposes. The estimated groundwater reserve of Nepal is 7 km^3 per year, of which 1.4 km^3 per year can be sustainably pumped to irrigate rainfed agricultural lands in the Tarai plains (Nepal et al., 2021). Amid the huge potential of these water resources, only a small part of it – estimated at 15 km^3 per year – has been utilized for irrigation. This is because of lack of infrastructure, technology and proper management, as well as financial challenges and extreme seasonal variation in the availability of water in the rivers (Government of Nepal, 2011).

Agriculture is the primary economic activity of Nepal. It provides 28% of gross domestic product and employs about 66% of the total population (Ratha et al., 2018). Rice is the major monsoon crop and is grown at various altitudes and climatic conditions. Among the five major physiographic regions (Tarai, Siwalik hills, Mid-Hills, lower mountains and higher mountains) about three-quarters of the total rice-growing area is in the Tarai. Wheat is the major winter cereal crop, with more than 80% of wheat grown together with rice in a rotational system (Subedi et al., 2020). Maize is another important crop in the Mid-Hills, covering about 80% of the croplands in the hills (Sharma, 2001). Maize is also suitable for the Tarai, and its cultivation during the winter and spring seasons is increasing (Krupnik et al., 2021). Apart from rice, wheat and maize, the minor crops cultivated in Nepal are mustard, millet, barley, buckwheat, pulses, jute, cardamom and vegetables.

At present, only about 48% of cultivated land in Nepal has irrigation facilities of some kind, among which only about 39% has a year-round irrigation facility (IMP, 2019; Pandey et al., 2021). Moreover, even those agricultural areas defined as irrigated do not have sufficient water because of issues such as the malfunction of existing irrigation infrastructures and weak institutional capacity. Among these, irrigation expansion is limited mainly to the Tarai, which contributes more than 55% of total national cereal production in Nepal (Shrestha et al., 2013). Fifty-nine percent of total irrigated cropland is irrigated by a canal system, 22% by groundwater, and the remaining land by a combination of surface and groundwater (IMP, 2019; Pandey et al., 2021). The main source of canal irrigation is the medium and small rivers; the larger, perennial rivers are mostly left untapped (Government of Nepal, 2011). Moreover, many privately invested groundwater facilities are not reported, meaning that groundwater contribution is much higher than the statistics indicate. Groundwater recharge in the Tarai is estimated to be 8800 km^3 per year but only about 22% of that available in the region is being utilized (Shrestha et al., 2018). The existing data suggest that the Tarai region has sufficient water resources which could be extracted on a sustainable basis for irrigation but which is currently being underutilized (Shrestha et al., 2018).

Despite the availability of irrigation systems, some crops are still facing water stress, especially when smaller and medium-sized rivers are utilized as the main source of water (Thapa and Scott, 2019). Moreover, the construction of big irrigation projects is very costly and may not be economical everywhere. Leaving aside expansion of the irrigation system and construction of bigger irrigation projects therefore, crop productivity and profitability can also be increased by selecting suitable crops according to soil and climatic conditions, mixing and rotating crops, applying the appropriate amount of fertilizer at the right time, adopting suitable agricultural management practices, and the careful utilization of existing irrigation facilities in a sustainable manner. In other words, a rapid update of the sustainable irrigation framework is required to uplift Nepalese agriculture and increase productivity. Models like the Soil and Water Assessment Tool (SWAT) are used worldwide in making management-related decisions, and so the team used an analysis of SWAT modeling scenarios to determine a suitable mix of different cropping and management interventions. It then used model output of alternative scenarios to assess how different water use can impact crop productivity and water sustainability.

To develop a sustainable and inclusive scaling framework for farmer-led irrigation development in Nepal, the Cereal Systems Initiative for South Asia (CSISA) – Covid-19 Response and Resilience Activity has been implemented by International Maize and Wheat Improvement Center (CIMMYT), International Water Management Institute (IWMI), Texas A&M University (TAMU), and Cornell University, with the support of USAID. The Activity is focussed on sustainable irrigation development, considering how irrigation can increase resilience and generate income for smallholder farmers in the COVID-19 crisis-affected districts of the Feed the Future (FtF) Zone of Influence (ZoI) in Nepal. Ftf ZoI – the USAID-targeted regions/districts in Nepal – is an important region for the study because this is where the US government's global hunger and food security initiative intends to achieve the greatest household and individual level impacts on poverty, hunger and malnutrition.

The activities conducted as part of this Activity will help in developing a customized set of integrated modeling and scenario analyses to provide local, district and provincial level assessments of water resources that would affect the utilization of irrigation at a watershed scale. This water resource and irrigation sustainability assessment will be able to provide guidelines for the sustainable development of surface/groundwater irrigation to benefit COVID-19 crisis-impacted areas.

Status of irrigation development in Nepal

The Tarai region of Nepal is more suitable for agricultural production than the Mid-Hills and high mountains due to its flat terrain, fertile land, warm climate and easy access to irrigation water. About 65% of the irrigable land in Nepal is in the Tarai, and more than 300,000 ha of land within the Tarai region of the study area have irrigation facilities, among which 72% of the land is irrigated by surface irrigation systems and 28% by the groundwater-based system (Pandey et al., 2021). Among the four major river basins in the study area, only 3% of the available water from the Mahakali river is utilized for irrigation while water utilization from the Karnali, West Rapti and Babai rivers are 7%, 12% and 77% respectively (Pandey et al., 2021). Large rivers such as Mahakali and Karnali can provide enough water throughout the season for surface irrigation, whereas small and medium rivers like Babai and West Rapti can only provide water during the monsoon season.

Despite the government major irrigation development projects, groundwater is also a good source of irrigation in the Tarai and Inner Tarai regions of Nepal (Pathak, 2018). Currently however, groundwater irrigation is limited to very small agricultural areas of land. The Government of Nepal considers that more than 80% of the groundwater that has not been utilized can be sustainably abstracted for groundwater irrigation (Urfels et al., 2020). However, many groundwater facilities established with private investment are not reported though 40% of irrigated areas in Tarai are provided by groundwater sources (Urfels et al., 2020). The maximum current usage of groundwater for irrigation at the district level is in Kanchanpur (53%) and the minimum in Bardiya (13%). The groundwater irrigation plan is based on the shortage of surface water from irrigation projects, as the area which cannot be irrigated by surface water will be irrigated by groundwater (IMP, 2019).

Many water-resource and irrigation-development Activities have been implemented in the FtF ZoI by the Government of Nepal, either solely or in collaboration with various development partners and research institutes, including the United States Agency for International Development (USAID), Asian Development Bank (ADB), Government of Switzerland, and International Water Management Institute (IWMI). Some of the major projects in the region are the Prime Minister Agriculture Modernization Project (2016–26) funded solely by the Government of Nepal, the small irrigation program (2015–20) funded by the Government of Switzerland, Community Irrigation Project (CIP) (2010–18) funded by ADB, Digo Jal Bikas (DJB) Project (2016–19), PAANI program (2016–21) and Knowledge-Based Integrated Sustainable Agriculture in Nepal (KISAN) project (2017–22) funded by USAID. USAID is focussed on implementing irrigation development activities through its Activites such as like DJB, PAANI and KISAN. Details about the status of irrigation development and under construction projects in Nepal can be found in the review report (Pandey et al., 2021).

Climate change studies

In addition to building resilience to existing patterns of climate variability, Nepal is also projected to be significantly affected by climatic change in the future (IPCC AR6, Pandey), with more extreme events such as high rainfall days, drought and heatwaves likely to impact the country's agriculture and water resources. This study therefore modelled scenarios on irrigation sustainability and crop productivity for the near (2022–35) and mid-term (2036-2050) futures.

The study used climate change scenarios derived from the global circulation model (GCM) for predicting future climates, as these can provide reliable information regarding historical, current, and future climate trends over long periods (Gonzalez et al., 2010). However, regional climate models (RCMs) – which have higher spatial resolution compared to GCMs – are more suitable for climate change study in our study area, which has a large variation in topography (Flato et al., 2014). Among four different representative concentration pathways (RCPs), RCP 4.5 (which represents slower global warming and limited climate change) and RCP 8.5 (which represents rapid global warming as climate change policies are not enforced to limit greenhouse gas emissions) were used in this study (Van Vuuren et al., 2011).

The objective of the study

Before running the model and simulation, and analyzing the results of various management practices in watersheds, it is important to select the appropriate scenarios carefully. This study analyses the sustainability of water resources for irrigation at the local, district and provincial levels through the implementation of unique scenarios that are favourable to the socio-economic and hydroclimatic contexts of the FtF ZoI districts in Nepal. The scenario modeling approach examines the differences in model outputs from various possible scenarios and facilitates the investigation of their impact on water resource sustainability and crop productivity. Moreover, the existing, although limited, data suggest that the Tarai region of the FtF ZoI districts in Nepal has sufficient water resources which could be extracted on a sustainable basis for irrigation, and which is currently being underutilized (Shrestha et al., 2018). This study evaluates these hypotheses using a modeling approach and suggests the maximum extent of surface/groundwater that can be withdrawn sustainably for irrigation.

The key objectives of this study were to:

(1) decide on appropriately integrated modeling scenarios to be implemented in watersheds,

(2) assess the potential impacts of modelling scenarios on existing water resources and crop production,

(3) analyze the sustainability of the modeling scenarios, and

(4) discuss the changes needed in policy, practice and investments at local, district and provincial levels for sustainable irrigation development and expansion of crop production.

2. Materials and methods

Study area

The study was conducted in four watersheds: Mahakali, Karnali, Babai and West Rapti, in the Lumbini and Sudurpaschim provinces of Nepal. It concentrated mainly on the Tarai and some Mid-Hills districts located within the FtF ZoI in the Lumbini and Sudurpaschim provinces (in Nepal, FtF currently works in 21 districts in the Lumbini, Karnali, Sudurpaschim and Bagmati provinces). Administratively, the FtF ZoI in Lumbini and Sudurpaschim provinces consists of 16 districts, of which 10 districts are in the Mid-Hills region and six in the Tarai region. Altogether, 165 local governments – five sub-metropolitan cities (*upamahanagarpalikas*), 57 municipalities (*nagaurpalikas*) and 103 rural municipalities (*gaunpalikas*) – are enclosed within the FtF ZoI in the study area. The location of the study area and watersheds are presented in Figure 2-1.

Among the river systems of our study watersheds, Karnali and Mahakali are snow-fed perennial rivers while West Rapti and Babai are rain- and spring-fed rivers originating in the Siwalik hill region also known as the Chure range. The Chure range, extending from the Indus river (in Pakistan) in the west to the Brahmaputra river (in India) in the east, covers about 12% of the total land area of Nepal and plays an important role in the conservation of Tarai's surface and groundwater resources. All the rivers, flowing from north to south, deposit heavy sediments and debris on the plain Tarai region providing it with fertile alluvial soil. Mahakali river originates from the mountains in Uttarakhand province of India, drains a large portion of Sudurpaschim province of Nepal and flows along the western border with India. Similarly, the Karnali river originates on the Tibetan plateau, drains the whole Karnali province along with portions of Lumbini and Sudurpaschim provinces and mixes with the Sharda (Mahakali) river in India. The West Rapti river originates from a ridgeline midway between the western Dhaulagiri mountain and the Chure range, flows initially eastwards and then takes a southeastern route to enter India, draining districts of Lumbini province. Similarly, the Babai river originates in and completely drains the Inner Tarai Dang valley and part of Bardiya district in Lumbini province.

About 70% of the study's watersheds are covered by forest and about 20% by agricultural land. Rice is the major monsoon crop and wheat is the major winter crop grown together with rice in rotation in the Tarai region. Maize is the major crop in the Mid-Hills and is also suitable for cultivation in the Tarai during the

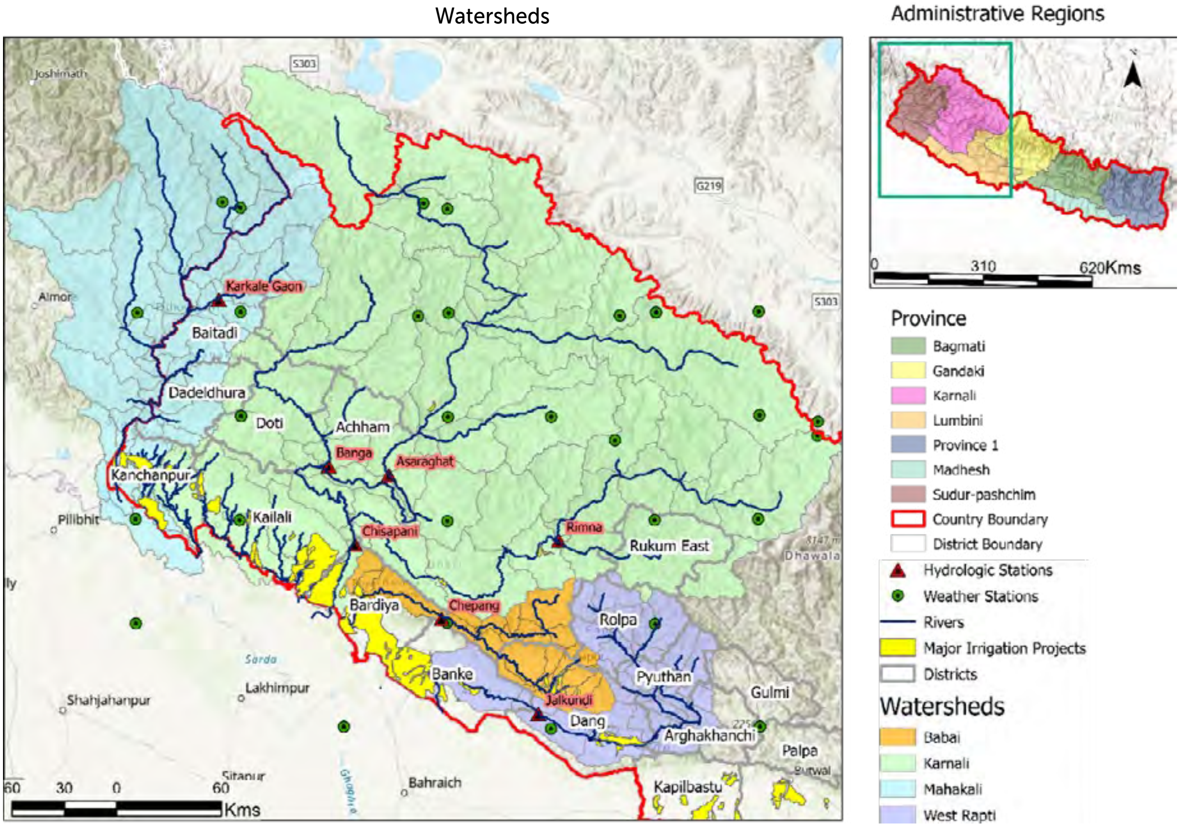

Figure 2-1. Area considered by the study: the four major watersheds (Mahakali, Karnali Babai and West Rapti), river network, hydrologic and meteorologic stations, and administrative regions.

winter and spring seasons. Along with rice, wheat and maize, mustard, mungbean, lentils, mungbean and vegetables are also grown in a certain part of the watershed. The percentage of irrigated land in the watersheds ranges from just 3% to 10%. The area occupied by the watersheds, and the part of rainfed and cultivated lands within the watershed is presented in Table 2-1.

There is a remarkable diversity in the topography of the study area, as elevation ranges from less than 100 m to over 8000 m above mean sea level. In line with Nepal's major physiographic regions, districts of the study area are also divided into the mountainous region (above 5000 m), Mid-Hills (1400 to 5000 m) and the Tarai/smaller hills (below 1400 m). As the climate depends on both elevation and latitude, the climatic zone of the study area ranges from a tropical climate in the Tarai region to an alpine climate in the mountainous region where the temperature is always below freezing point and the surface is covered by evergreen snow and ice. The Mid-Hills region has a subtropical monsoon climate. Most of the rainfall occurs from June to September. Although the study area receives abundant precipitation annually, rainfall distribution is very uneven due to the monsoon climate and the extreme topography. Average precipitation, and maximum and minimum temperature of the cities (Mahendranagar in the Tarai region and Dang in the Mid-Hills region) is presented in Figure 2-2.

Table 2-1. Watershed area along with a portion of rainfed and cultivated agricultural lands (ICIMOD, 2022).

Watershed	Watershed area (ha)	Area of rainfed cultivated land (ha)	Percentage of rainfed cultivated land	Area of irrigated cultivated land(ha)	Percentage of irrigated cultivated land
Karnali	4989216	593717	12%	156661	3%
Mahakali	1737664	255402	15%	88152	5%
Babai	332916	100101	30%	33168	10%
West Rapti	625328	186348	30%	16834	3%

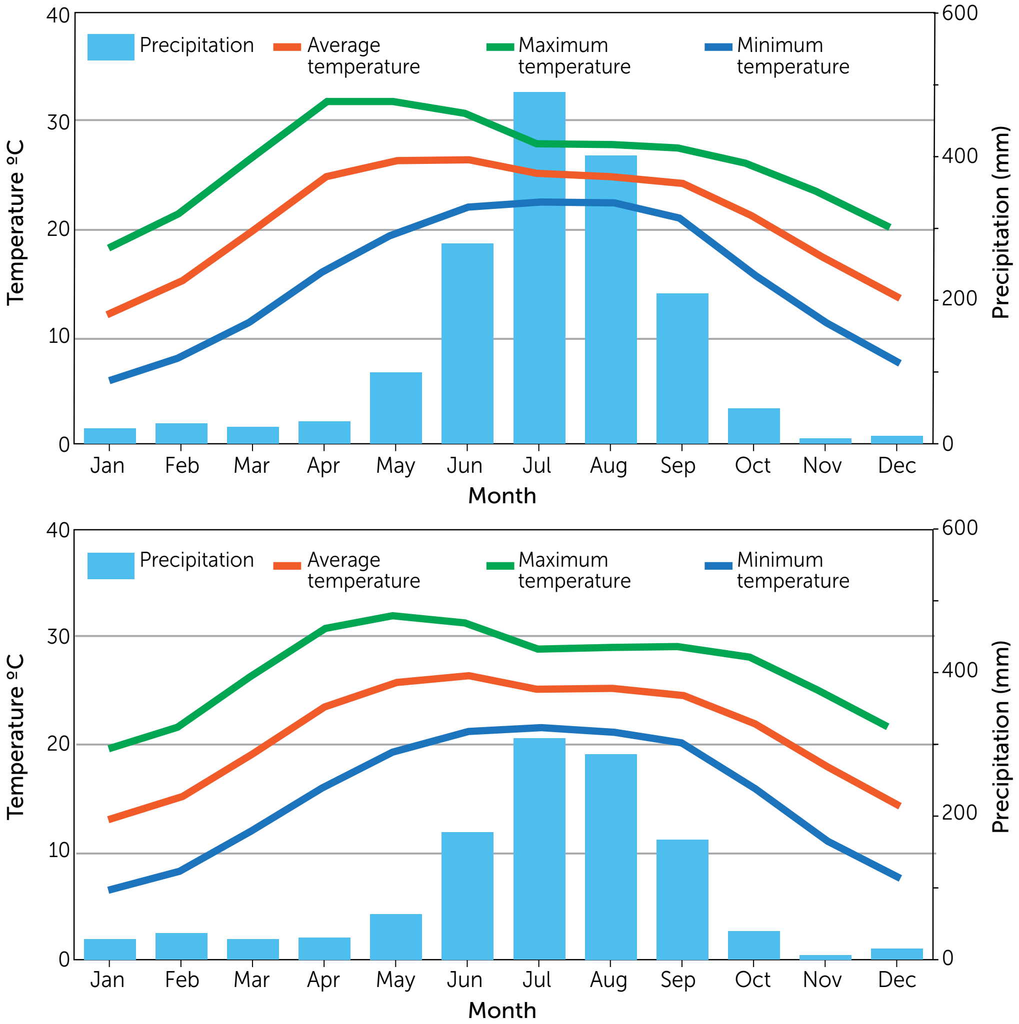

Figure 2-2. Average monthly precipitation, minimum and maximum temperatures in Mahendranagar of Tarai (upper) and Ghorahi of Mid-Hills region (lower)

Modeling approach

The first step in this study was to identify appropriate modeling scenarios for the study area, based on the combination of crop suitability, crop diversification potential, market access and interest of stakeholders. Modeling scenarios were selected according to the feasibility of crops in the region according to topography, climatic condition, irrigation infrastructure and soil types, based on discussions among project team members during a series of meetings, opinions of professionals working in the area for a good length of time, and opinion of stakeholders during the number of scenario planning workshops conducted at the provincial and national level. After the identification of modeling scenarios, four watersheds (Mahakali, Karnali, Babai and West Rapti) were delineated using a void-filled Shuttle Radar Topography Mission (SRTM, 2021) Digital Elevation Model (DEM) of 1 arc-second (30 m) resolution. The model was developed by incorporating biophysical data, such as land use and land cover (LULC), soil and climate (precipitation, temperature, relative humidity, solar radiation) information (Annex 1). Agricultural management data such as planting/harvesting schedules and information on irrigation, tillage, fertilization and management, obtained from a Cereal Systems Initiative for South Asia (CSISA) survey and discussion with project team members/agricultural experts working in the area, were fed into the model to develop a baseline model. The models were then calibrated and validated for hydrology by adjusting several different parameters (Annex 2) using streamflow data at different gauging stations located within the watersheds. Similarly, the model was calibrated for (1) change in shallow groundwater depth, using pre- and post-monsoon depth of observation well, and (2) crop yield using district-level rice and wheat yield data (rice and wheat are the dominant crops cultivated in the area. Appropriate spatially targeted crop rotation and irrigation development scenarios (identified from regular meetings, scenario planning workshops and expert opinion) were implemented in the specific sub-basins of the watershed. The biophysical impacts of the interventions and their benefit on crop production were examined at watershed and field scales. The schematic diagram of the methodologic approach is presented in Figure 2-3.

SWAT model

The Soil and Water Assessment Tool (SWAT) is a physically-based continuous time step-distributed parameter model developed to simulate the impacts of land management practices on water quality and quantity in the watershed, among diverse soil, land use and management conditions (Neitsch et al., 2011). SWATcan simulate hydrologic cycles, plant growth, nutrients, pesticides and bacteria at each sub-watershed, river segment and hydrologic response unit (HRU), the smallest unit of watershed consisting of a specific type of land use, soil, slope and management operations. The modeling components of SWAT include hydrology, weather, soil erosion, nutrients, soil temperature, plant growth, pesticides, bacteria and agricultural management. It can be applied to a wide range of watersheds from a small field to a large river basin. Different interfaces of SWAT, such as ArcSWAT, QSWAT, are available for different GIS interfaces. Water balance is the chief driving force for each process within SWAT, such as streamflow, sediment, nutrient, pesticides and pathogen transport and plant growth.

Data

The basic inputs required by the SWAT model include geospatial data such as a digital elevation model (DEM), land use and land cover (LULC),

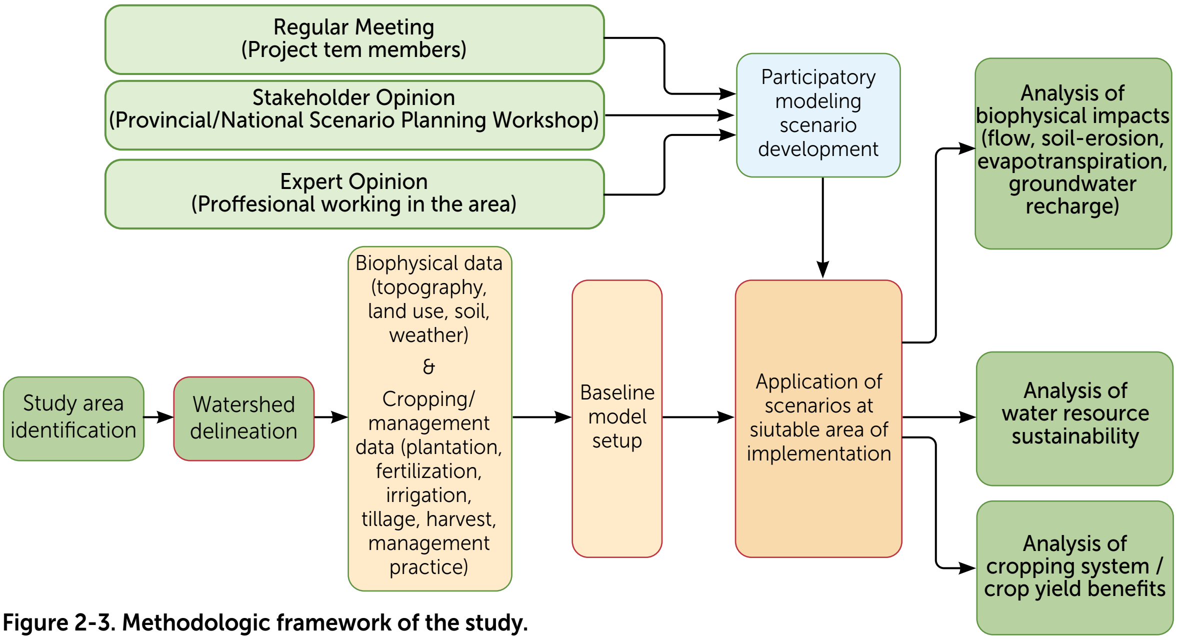

Figure 2-3. Methodologic framework of the study.

soil and meteorologic information (precipitation, minimum and maximum temperature, relative humidity, solar radiation, and wind speed), hydrologic and water quality information, along with agricultural cropping and management data.

A void-filled Shuttle Radar Topography Mission (SRTM, 2021) DEM of 1 arc-second (30 m) resolution, downloaded from USGS Earth Explorer (USGS, 2021) was used for the model setup and watershed delineation. Similarly, the soil data, prepared from the 1 km ISRIC global soil grid using the pedotransfer function (Saxton and Rawls, 2006) function was used. The raster data provided information on, among others, texture, bulk density, water content, pH, cation exchange capacity, and electrical conductivity for six different layers of soil, and were obtained from the World Soil Information Service database developed and maintained by ISRIC (ISRIC, 2021). Likewise, the LULC data for the entire study area was prepared using crop mask layers obtained from CIMMYT and a LULC map available from the International Center for Integrated Mountain Development (ICIMOD, 2010). Other geospatial data such as administrative boundaries, major rivers, highways, irrigation canals and major cities were obtained from the International Water Management Institute (IWMI, 2021) data portal and open data sources.

The weather data (precipitation, maximum and minimum temperature) for 35 different meteorologic stations (Figure 2-1) were obtained from the Department of Hydrology and Meteorology, Kathmandu, Nepal. As an alternative source, precipitation data for the study areas were also extracted from the global precipitation satellite grid, Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), which is relatively high spatial resolution quasi-global precipitation data with long-term temporal coverage from 1981 to near real-time. The processing chain combines both satellite and gauge precipitation estimates (Funk et al., 2015). The data from CHRIPS and the meteorological stations were blended.

Streamflow data for seven gauging stations (Figure 2-1, Table 2-2), used for the streamflow calibration of the models, were obtained from the Department of Hydrology and Meteorology, Kathmandu, Nepal (DHM, 2021).

Table 2-2. List of available hydrological data.

Station	Watershed	Period	Elevation
Karkale Gaon	Mahakali	1965–2013	685
Asaraghat	Karnali	1962–2014	629
Banga	Karnali	1963–2014	328
Rimna	Karnali	1977–2014	772
Chisapani	Karnali	1962–2014	191
Chepang	Babai	1990–2013	325
Jalkundi	West Rapti	1964–2006	218

Model setup

The sub-watershed and drainage network delineation for all the watersheds in the study area was performed using the ArcSWAT interface based on DEM data. Sub-watersheds were further sub-divided into HRUs based on the land use and soil type information. For snow-fed watersheds like Karnali and Mahakali, five elevation bands were set up for the sub-basins dominated by snow and glaciers. Daily weather data for precipitation and maximum and minimum temperature, along with a user-defined weather generator database were provided to the model for the entire simulation period. Among different methods available for the estimation of surface runoff, this study used the SCS curve number method (among the available methods of SCS Curve Number or Green and Ampt) for the estimation of surface runoff, the Hargreaves method (among the available methods of Hargreaves, Penman-Monteith and Priestley) for the estimation of potential evapotranspiration, and variable storage method (among the available methods of variable storage or Muskingum method) for the estimation of channel water routing. A baseline model was developed considering all the crops currently grown in the study area. The information on tillage, plantation, fertilization, irrigation, harvest, and current management practices were incorporated into the model using the ArcSWAT interface. In the Tarai region, areas not covered by canal irrigation systems were assumed to be covered by shallow groundwater irrigation.

Agricultural cropping and management operation

Rice was the main monsoon season crop and wheat the main dry season crop in Tarai. Similarly, maize was the main monsoon crop in hilly districts. The data on planting and harvesting, tillage, fertilization, irrigation and other management operations for some crops were based on expert opinion (personal communication), a CSISA survey, and other sources. For example, the data for crops such as tomato, potato and mungbean was obtained from Activity team members and agricultural experts working in the area. The detailed cropping schedule adopted for crops, monsoon rice, spring rice, monsoon maize, winter wheat, winter maize, tomato, potato, lentil and mungbean established in the Tarai and Mid-Hills regions is presented in Annex C.

Model calibration and validation

Model calibration and validation must be performed before analyzing any simulation output obtained from the model as these help in reducing model prediction uncertainty and increasing the accuracy of the simulations (Arnold et al., 2012). The SWAT models for the watersheds – Mahakali, Karnali, Babai and West Rapti – were calibrated and validated for hydrology using high-quality flow data obtained from gauging stations (Figure 2-1, Table 2-2) located within the watersheds.

The Sequential Uncertainty Fitting (SUFI-2) algorithm within the auto-calibration tool, SWAT Calibration and Uncertainty Procedures (SWAT-CUP) were applied for the hydrologic calibration of SWAT. NSE was used as an objective function for optimization of the parameter (Annex 2), as it is one of the most reliable and widely used statistics in assessing the goodness of fit. Similarly, R^2 was used to assess calibration and validation performance for groundwater depth and crop yield.

The statistics obtained during monthly streamflow calibration and validation of SWAT for four watersheds suggested that the model performance for streamflow simulation was in general very good, based on performance rating criteria developed by Moriasi et al., (2007), as the NSE and R^2 values, were greater than 0.65 for the majority of the stations (Table 2-3). Similarly, the absolute value of PBIAS was less than 25%, which suggested that streamflow simulated by SWAT does not have significant bias.

Moreover, the graphical analysis of observed and simulated flow rates also showed good agreement between simulated and observed streamflow at all the gauging stations within the four watersheds during both calibration and validation periods, as Figures 2-4(a), 2-5(a), 2-6(a) and 2-7(a) show. The flow duration curve (FDC), obtained for observed and simulated streamflow, and which gives an estimation of the fraction of the time at which the stream has exceeded a certain flow, shows that the model has simulated baseflow satisfactorily, as shown in Figures 2-4(b), 2-5(b), 2-6(b) and 2-7(b).

The models were calibrated for change in groundwater depth, using the observed pre- and post-monsoon depths of an observation well. Groundwater depth change calibration was conducted for different wells within the watershed. The difference in groundwater depth in SWAT was obtained from the difference in groundwater recharge. Assuming storativity of 0.3, groundwater fluctuation was 3.3 m per m of groundwater recharge when there was no discharge to surface water or deep aquifers. The observed and simulated groundwater depth change showed good agreement (R2=0.81 for Balapur well in Banke district) (Figure 2-8 a) and R2=0.52 for Bhaisawa well located in Dang district (Figure 2-9 b).

Similarly, model calibration and validation for crop yield were performed using observed district-wise national crop production data (Fig 2-9). Although average observed and simulated crop yields were quite comparable, there are considerable differences between observed and simulated crop yields. This is basically because of the uncertainty in observed data. As the observed crop yield data are

Table 2-3. Model performance for streamflow simulation during both calibration and validation periods at the four watersheds.

Watershed	Station		Calibration	Validation
Mahakali	Karkalegaon (gauging station: 120)	R^2	0.69	0.67
		NSE	0.68	0.67
		PBIAS	8.1	-1.3
Karnali	Chisapani (gauging station: 280)	R^2	0.81	0.82
		NSE	0.66	0.75
		PBIAS	-3.6	1.2
	Banga (gauging station: 260)	R^2	0.76	0.59
		NSE	0.75	0.58
		PBIAS	-10.6	-9.1
	Rimna (gauging station: 265)	R^2	0.78	0.82
		NSE	0.44	0.60
		PBIAS	17.3	20.7
Babai	Chepang (gauging station: 290)	R^2	0.78	0.73
		NSE	0.76	0.42
		PBIAS	-0.6	36.9
West Rapti	Jalkundi (gauging station: 360)	R^2	0.82	0.70
		NSE	0.77	0.67
		PBIAS	-12.7	-16.9

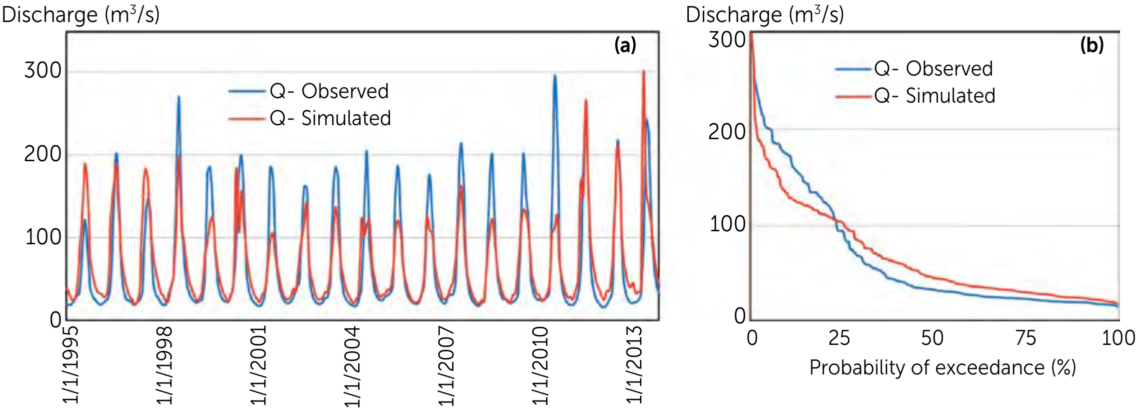

Figure 2-4. Comparison of observed and simulated streamflow (left) and flow duration curve (right) at Karkalegaon station (gauging station: 120) located near sub-basin 10 of the Mahakali watershed.

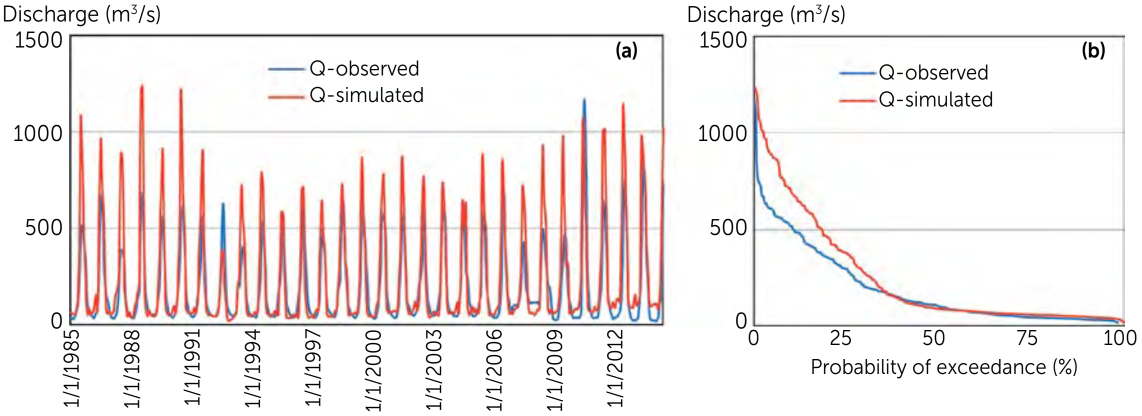

Figure 2-5. Comparison of observed and simulated streamflow (left) and flow duration curve (right) at Chisapani station (gauging station: 280) located near sub-basin 43 of the Karnali watershed.

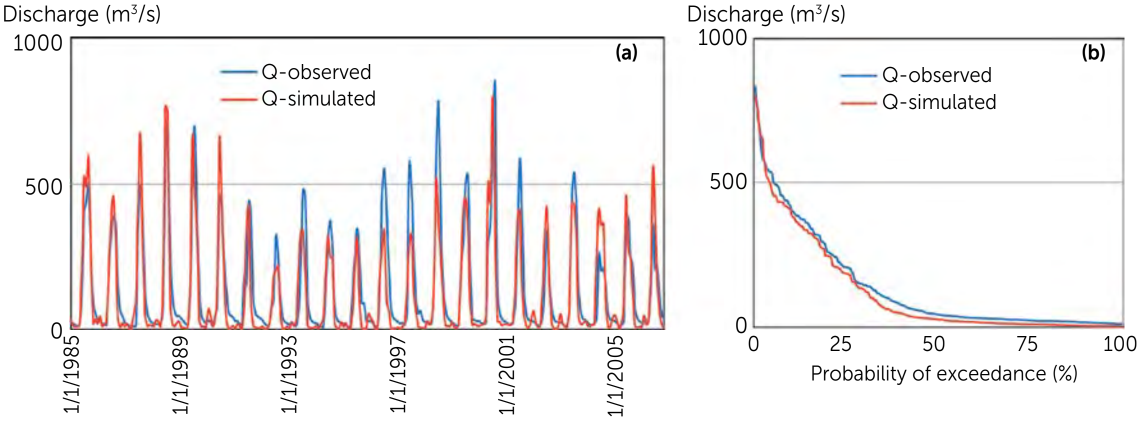

Figure 2-6. Comparison of observed and simulated streamflow (left) and flow duration curve (right) at Chepang station (gauging station: 290) located near sub-basin 11 of the Babai watershed.

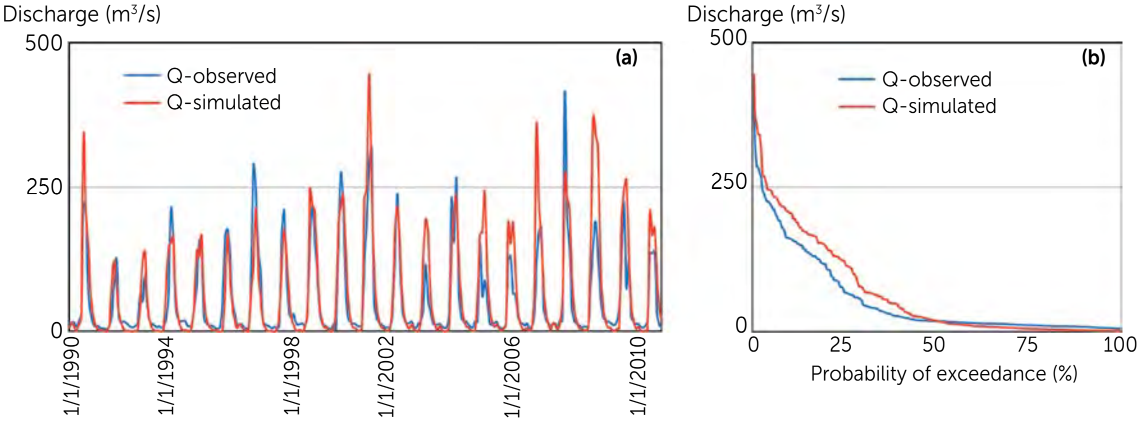

Figure 2-7. Comparison of observed and simulated streamflow (left), and flow duration curve (right) at Jalkundi station (gauging station: 360) located near sub-basin 26 of the West Rapti watershed.

not spatial, the regional average of data collected through the survey may not represent the spatial crop yield simulated by SWAT. Moreover, SWAT averages the crop yield by sub-basin, and taking crop yield data for each sub-basin to obtain district-wise average crop yield also provides uncertainty in crop yield estimation. Likewise, the national time-series of crop yield data itself is based on model estimates and contains many uncertainties, and thus may not agree with model simulations in some years. For example, the model prediction of wheat yield was significantly higher during 2011, while that during 2020 was considerably lower than the observed data (Figure 2-9 (b)).

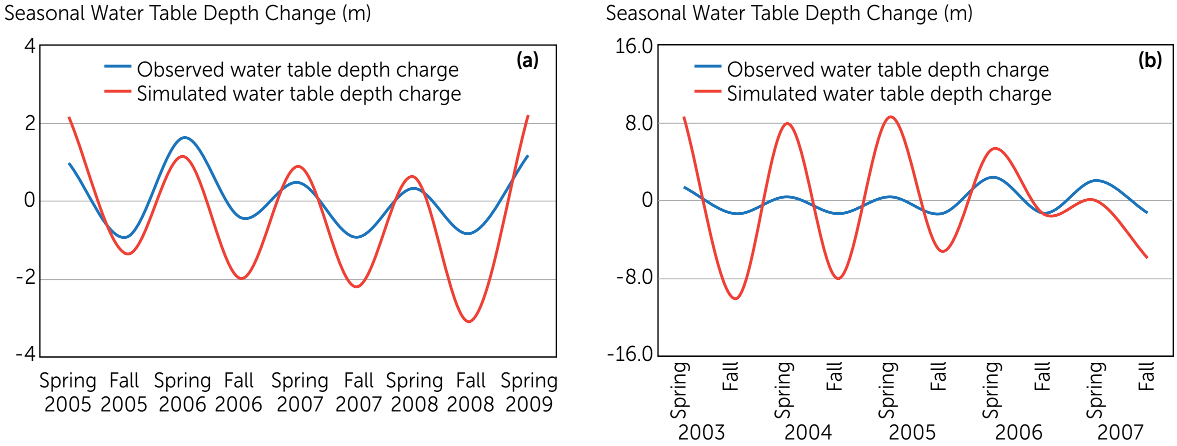

Figure 2-8. Comparison of observed and simulated seasonal water table depth change at Balapur well in Banke district (left) and Bhaisawa well in Dang district (right).

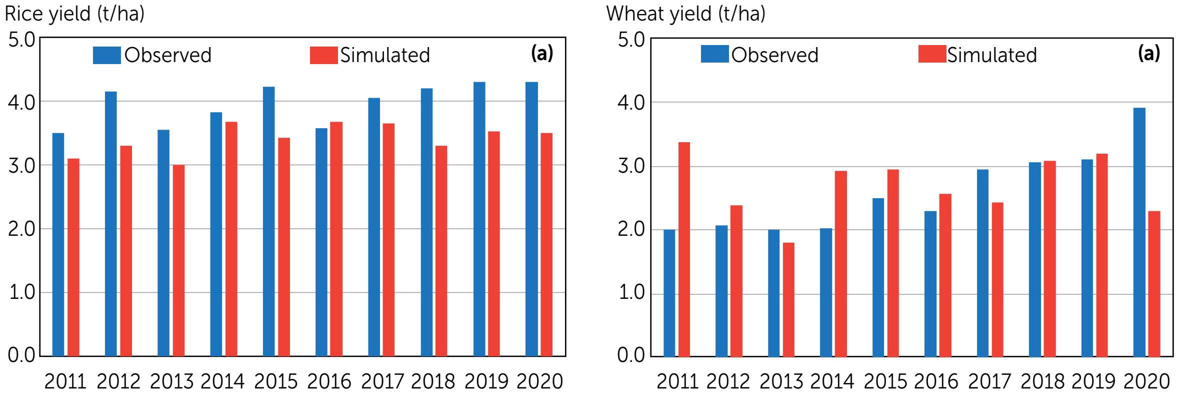

Figure 2-9. Comparison of observed and simulated rice yield in Bardiya district (left) and wheat yield at Kailali district (right).

Participatory development of alternate scenarios

Rice and wheat are the most widely cultivated cereal crops in Nepal. Stakeholders recommended closing the yield gap in rice and wheat crops by developing a proper irrigation system; this is also a policy priority for Government. Apart from the monsoon season, rice cultivation in the spring season is also of great interest, as its expansion at this time is a recent agricultural development goal set by Government (Bhandari et al., 2017). One of the scenarios (suggesting rainfed lentil could be replaced by maize in the winter season if irrigation facilities were available) could be implemented to improve overall crop production by extending cultivation into fallow land. Similarly, with the facility of a proper irrigation system, three crops a year (such as rice–wheat–mung bean and rice–vegetable–rice) could be racticed to improve overall agricultural production, instead of single- and double-cropping systems; however, environmental sustainability must also be investigated. The study also developed unique scenarios favourable to the socio-economic and hydroclimatic contexts of the study area districts. It also considered the scenario of replacing rainfed *rabi* crops with horticultural crops to improve water productivity and improve household income, as horticultural crops are high-value crops.

To estimate the impacts of management operations on sustainable irrigation and crop production, several modeling scenarios (Table 2-4) were identified and decided based on a combination of crop suitability, crop diversification potential, market access, and interest of stakeholders. The scenarios were selected according to the feasibility of crops in the region according to topography, climatic condition, irrigation infrastructure, and soil types, based on discussions among project team members during a series of meetings, the experience of professionals working in the area for a long time, the interest of the donor agency (USAID), and opinion of stakeholders during several scenario planning workshops conducted at the provincial and national levels.

The scenario which developed a proper irrigation system to close the yield gap in the rice–wheat system was implemented in the Tarai (Dang, Banke, Bardiya, Kailai, Kanchanpur) districts of the study region (Fig 2-10). Increasing rice and wheat yields is a policy priority for the Government of Nepal.

Similarly, the scenario of cultivating vegetables between monsoon and spring rice was implemented in the south-western sub-basins of Mahakali and south-eastern sub-basins of Karnali watersheds, falling in Bardiya and Kanchanpur

Table 2-4. Scenarios and their implementation in different districts

	Description	Implementation districts	Area affected by the scenario (ha)
Scenario 1	Closing the yield gap in the rice–wheat system	Dang, Banke, Bardiya, Kailai, Kanchanpur	724,940
Scenario 2	Cultivating vegetables between *kharif* and spring rice	Bardiya and Kanchanpur	63,243
Scenario 3	Replacing rainfed-lentil and fallow land with irrigated maize	Dang and Kailali	73,653
Scenario 4	Using an intensified triple-cropping instead of double-cropping system	Kailali and Banke	375,046
Scenario 5	Replacing rainfed *rabi* crops with horticultural crops	Rolpa and Argakhanchi (hilly districts) Dang (Tarai districts)	99,061

districts, respectively (Figure 2-10). This was because Baraiya (Lumbini province) and Kanchanpur (Sudurpaschim province) are potential districts for this system, where rice is intensively grown both during monsoon and spring seasons. The government has also implemented a subsidy program in these districts to expand the acreage of spring rice and thus to increase overall yield and make the country self-reliant on food grain.

Similarly, a scenario was developed by introducing irrigated maize in place of rainfed lentil and fallow land in Kailali (the southern sub-basins of Karnali watershed) and Dang (the southwestern sub-basins of Babai and West Rapti watersheds) (Figure 2-10) districts of Sudurpaschim and Lumbini provinces, hotspot areas for lentil production. As most of the lentil fields are rainfed and some areas in the region are currently fallow during the winter season due to the unavailability of irrigation facilities, they can be replaced by irrigated maize to improve overall crop production with sufficient irrigation facilities in the winter season.

In the same way, mung bean was introduced as a third crop between rice and wheat in sub-basins located in Kailali district (the southern sub-basins of Karnali watershed) and Dang district (the southern sub-basins of West Rapti watershed) of the study area (Figure 2-10). This could be achieved through the expansion of irrigation facilities for use in the winter and spring growing seasons, as a triple-cropping pattern had already beenracticedd in some of the areas in these districts. As mung bean requires a relatively shorter number of days to mature, it can be a convenient third crop to cultivate in a year.

This scenario replacing rainfed-*rabi* crops with horticultural crops was implemented in the hilly and Tarai regions of the West Rapti watershed (Rolpa, Argakhanchi and Dang districts) (Figure 2-14) as suggested by the stakeholders to implement in the urban sub-basin, as this has market availability and accessibility to roads. Moreover, Dang district has a high potential for horticultural crops.

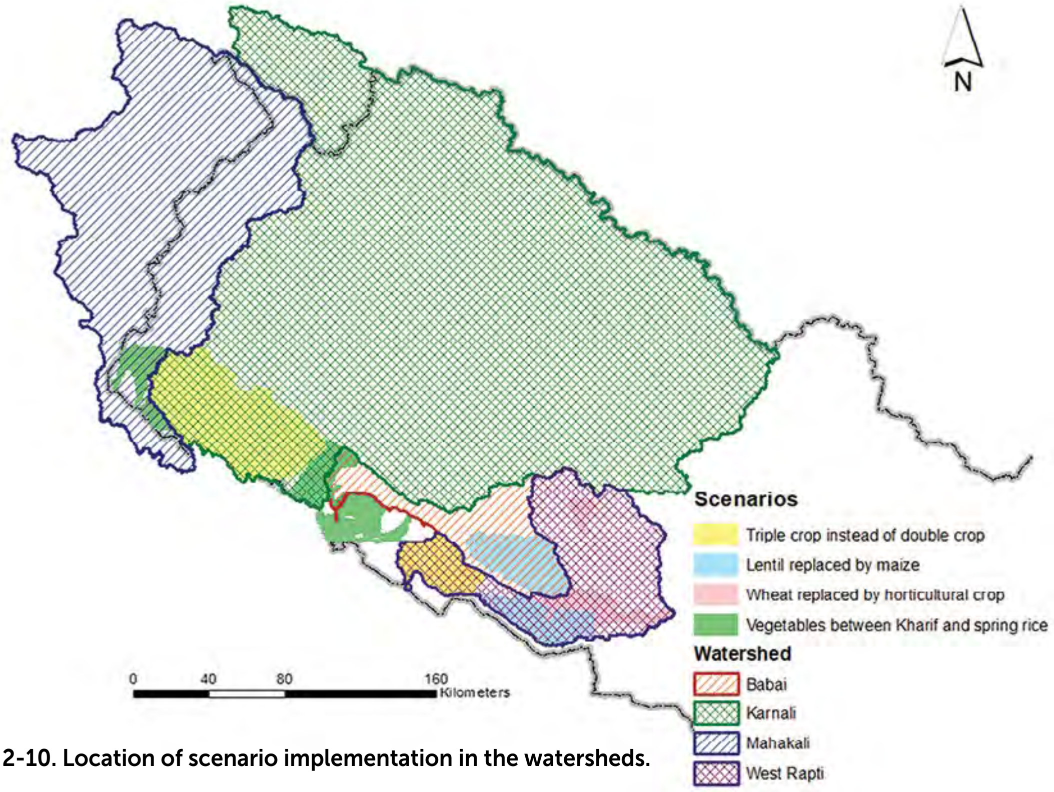

Figure 2-10. Location of scenario implementation in the watersheds.

The selected scenarios were used to analyze the effects of different scenarios on streamflow, surface water, groundwater level and crop production. The location for the feasibility of these scenarios was selected based on discussions among project team members, opinions of stakeholders during scenario planning workshops (conducted at provincial and national levels), and the experience of experts working in the field. Results obtained from the analysis of these scenarios may be integrated into the framework enabling identification of irrigation expansion potential and the design of sustainable and inclusive irrigation projects, as these results can inform policy makers, facilitating the devising of sustainable land and water management practices.

Scenario 1: Closing the yield gap in the rice–wheat system

The main factor responsible for increasing the productivity of rice is assumed to be the availability of sufficient water for irrigation, either from surface or groundwater, or a combination of both. The availability of surface irrigation was identified using the Irrigation Master Plan[1] map. In this study, combinations of both groundwater and surface water irrigation were supplied. Groundwater irrigation was adopted in the areas where surface water became limited due to seasonality and access to streams, for example in areas that are far from rivers. Only flood irrigation was considered for both surface and groundwater in the rice–wheat system, as this is the most widespread method of irrigation in Nepal. The irrigation schedule and efficiency for rice and wheat were based on expert opinion. For surface irrigation, the current Irrigation Master Plan system was assumed to be partially implemented and thus sub-scenarios and alternative scenarios were developed assuming 25%, 50% and 75% of the Masterplan areas to be functional. An optimal amount of fertilizer was applied to maximize crop yield, as irrigation alone is unlikely to mprove crop yield. The crop yield in tons per ha and total aggregate production at district and province levels were analyzed. Apart from that, the amount of surface/groundwater availability and recharge were analyzed for each scenario.

Scenario 2: Cultivating vegetables between *kharif* and spring rice

Baraiya distict (Lumbini province) and Kanchanpur district (Sudurpaschim province) have potential for adding a vegetable crop between two rice harvest. Rice is intensively grown crop in Bardiya and Kanchanpur during both monsoon and spring seasons as per the Government's priority of expanding the acreage of spring rice. Expansion of spring rice in these districts can help in increasing overall rice yield, making the Nepal self-reliant in rice. As the total length of time between harvesting monsoon rice and planting spring rice is less than 90 days, shorter duration vegetables were selected for this scenario. including tomato, which was chosen as a reference vegetable crop. Vegetables were planted in November and harvested in January, spring rice was planted in mid-January and harvested in early June, and monsoon rice was planted in mid-June and harvested in late October. Besides having shorter growing periods, vegetables are high-value crops and provide different types of vitamins and minerals. Considering vegetables in the scenarios thus helps to improve household income and nutrition.

Scenario 3: Replacing rainfed lentil and fallow land with irrigated maize

Dang and Kailali districts (Lumbini province) are hotspot areas for lentil production. As the winter and spring seasons have short growing period seasons, lentil is a suitable crop to cultivate. Moreover, lentil has a high economic value and environmental benefits such as improving soil fertility. Most lentil fields are, with some areas in the region are currently fallow during the winter season due to the unavailability of irrigation facilities. However, with sufficient irrigation facilities in the winter season, croplands cultivating rainfed lentils and which are fallow in winter can be replaced by irrigated maize to improve overall crop production. For *ex-ante* assessment, we assumed the availability of an irrigation system and implemented the scenario to replace existing lentil and fallow lands with maize to analyze the feasibility of expanding irrigation to the areas where it is not yet available. Irrigation was provided to the slightly sloped fallow agricultural lands in the sub-basin to expand maize cultivation.

Scenario 4: Intensified triple-cropping instead of a double-cropping system

Rice–wheat is the predominant double-cropping pattern in the Tarai region of Nepal; the triple-cropping pattern is also practiced in some areas. Mung bean was introduced as a third crop between rice and wheat as it requires a relatively shorter number of days to mature, making it convenient as a third crop to cultivate in a year. This scenario evaluated the sustainability of the triple-cropping system instead of the double-cropping system was analyzed and the percentage of the total area that could be sustainably cultivated with the third crop with available water resources.

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[1] Irrigation Master plan is the national planning document that identifies and ranks the list of potential irrigation projects to be implemented throughout the country, prepared by the Department of Water Resources and Irrigation Ministry of Energy, Water Resources, and Irrigation Government of Nepal (IMP, 2019).

Scenario 5: Replacing rainfed *rabi* crops with horticultural crops

Horticultural crops are high-value crops that can improve the level of income and livelihood of rural farming households. During the provincial and national workshops, the stakeholders suggested that horticultural crops can be established in the urban sub-basin, where there is market availability and accessibility to roads. Moreover, the Dang district has a high potential for horticultural crops. The potato was used as a reference crop to represent horticultural crops grown in the sub-basins. As vegetable cultivation is often conducted in an orderly manner, an increased irrigation efficiency such as sprinkler or drip irrigation systems was assumed, in contrast to rice and wheat cultivation for which flood irrigation is often used.

Climate change analysis

Climate change is likely to impact the hydroclimatology of Nepal. For example, studies conducted in the Babai river watershed indicated that in the future, rainfall is likely to increase by 15% to 25%, temperature by 1.5°C to 4.7°C, minimum temperature by 2°C to 5°C, and annual river flow by 24% to 37% (Mishra et al., 2021). The basis for RCM selection for climate change impact assessment in this study was provided by (Dhaubanjar et al., 2020) evaluating nineteen different CORDEX RCMs in the Karnali basin, Nepal. Accordingly, this study used results from the NOAA_RegCM4 model for climate change studies, as it is one of the most widely used models for this region.

NOAA_RegCM4 RCM data was downloaded from the Coordinated Regional Downscaling Experiment for South Asia (CORDEX-SA) via The Earth System Grid Federation portal (ESGF, 2021). The study used the Representative Concentration Pathway (RCP) 4.5 which represents the medium emission scenario (Van Vuuren et al., 2011). It then used cMhyd (Climate Model data for hydrologic modeling) for bias correction and the preparation of simulated climate change input of precipitation and temperature (Rathjens et al., 2016). The same correction algorithm as used for historical conditions was used for future climatic conditions, as the bias correction algorithm for historical climate conditions is assumed to be applicable for the future climate in cMhyd. The bias-corrected daily precipitation and temperatures for future periods were then used in the calibrated and validated SWAT model. The effects of different scenarios on surface/groundwater sustainability and crop yield for Mahakali, Karnali, Babai and West Rapti watersheds were analyzed using climate data for the near future (2021 to 2035) and midterm future (2035 to 2050) periods. The Soil and Water Assessment Tool (SWAT) model has been applied broadly in numerous watersheds around the world to predict the impacts of climate change (Dhaubanjar et al., 2020; Wu and Johnston, 2007), including being used extensively in Nepal used to study the effect of climate change in different watersheds such as the Karnali, Babai, Bagmati and Koshi basins (Babel et al., 2014; Bhatta et al., 2019; Dahal et al., 2020; Mishra et al., 2021).

Sustainability of surface/groundwater resources

Under the most optimistic assumption, the groundwater resource is sustainable if the annual groundwater pumping rate is equal to the annual groundwater recharge rate. However, there are many uncertainties in the model prediction of recharge rate, which can vary greatly according to geological substrata, climate and topography. Thus a safe groundwater withdrawal limit, lower than the groundwater recharge rate, must be assumed for the sustainability analysis of groundwater resources (Lopez et al., 2022). Moreover, other uses of groundwater such as drinking and for domestic purposes must also be considered. Due to some uncertainties in model prediction, a factor of safety was considered to withdraw a safe amount of groundwater. Taking the 30% factor of safety for uncertainties and other use of groundwater, groundwater use was assumed to be sustainable when the required irrigation amount was less than 70% of the total annual groundwater recharge(Lopez et al., 2022).

Surface water is considered sustainable when the amount of water in the main river is not depleted greatly by irrigation for each season. Although the flow during the monsoon is high and is sufficient to divert water from most of the river to canals for surface irrigation, during pre and post-monsoon the flow may not be used for surface irrigation in most of the scenarios, as at least 30% of the total river discharge is left in the river for environmental flow requirements. The sustainability of different scenarios were computed by comparing the amount of water in the main river and analyzing the amount of water remaining after withdrawing water for irrigation in each season.

3. Results and discussions

The average annual discharge of Mahakali, Karnali, West Rapti and Babai rivers was 730 m^3/s 2990 m^3/s, 136 m^3/s, and 71 m^3/s respectively. Karnali watershed received the maximum annual rainfall (2283 mm) and Babai watershed the lowest (1631 mm). The average annual surface runoff and groundwater recharge were highest for the Mahakali watershed and comparatively lower for Karnali, Babai, and West Rapti watersheds. The annual actual evapotranspiration for the baseline scenario in the West Rapti watershed was highest at 702 mm and lowest for the Mahakali watershed at 400 mm. The summary of average precipitation, snowfall, snowmelt, surface runoff, evapotranspiration, groundwater recharge and water yield for four different watersheds in the study region is presented in Table 3.1.

The monsoon season in which most of the rain falls observed maximum flow than other seasons. The model output showed that snow-fed perennial rivers (Karnali and Mahakali) had sufficient water during the entire year; however, the water in the rain- and spring-fed rivers (West Rapti and Babai) was not sufficient for irrigation during the pre- and post-monsoon seasons. Mahakali river has two-thirds of its drainage area outside the boundary of Nepal and annual water availability of 10924 million m^3/year. The Karnali river with 94% of its drainage area in Nepal, has annual water availability of 71279 m^3/year. The annual water availability of West Rapti river is 7214 million m^3/year; Babai river had the lowest annual water availability of 3161 million m^3/year.

Analysis of Modeling Scenarios

Anaysis of the scenarios focussed on their effect on groundwater recharge and groundwater irrigation sustainability, as well as surface water availability and crop productivity. The impact on groundwater potential and its sustainability was analyzed by evaluating (1) depletion of groundwater reserves in the long run, and (2) comparison of annual groundwater recharge with irrigation requirement after excluding 30% of the groundwater recharge for irrigation as a sustainability safety measure. Similarly, the impact on surface water was conducted by comparing the amount of water remaining in the main river after withdrawing water for irrigation in each season. The impact on crop yield and total crop production was analyzed by comparing average yield and production for all five scenarios.

Scenario 1: Closing the yield gap in the rice–wheat system

Impact on groundwater resource

Both the rice–wheat rainfed and rice–wheat irrigated systems showed that the overall groundwater reserve for Mahakali watershed was stable (Figure 3-1). Although the irrigated rice–wheat system withdrew slightly more groundwater than the baseline scenario, the groundwater was observed to be replenished over the period due to recharge from the surface water irrigation contribution. The groundwater reserve was increased by 6 mm and the average annual groundwater recharge by 364 mm/year when 50% of the irrigation water was provided from surface water and 50% from the groundwater system in Mahakali watershed.

However, the groundwater reserve was depleted by 23 mm and the average annual groundwater recharge was increased by 1 mm when all the irrigation water for the rice–wheat system was provided from the groundwater source in West Rapti watershed (Figure 3-2). Although the groundwater recharge was observed to increase after irrigation due to infiltration, depletion of the groundwater reserve can have an impact on available groundwater in the future and eventually affect crop production with decreases in irrigated areas. The monsoon season crop (*kharif* rice) must therefore be supplemented with surface water irrigation whenever necessary to reduce groundwater irrigation demand in the West Rapti watershed.

Table 3-1. Summary of average precipitation, snowfall, snowmelt, surface runoff, evapotranspiration and groundwater recharge for four different watersheds.

Watershed	Area (ha)	Annual precipitation (mm)	Annual snowfall (mm)	Annual snowmelt (mm)	Annual surface runoff (mm)	Annual evapotranspiration (mm)	Annual ground water recharge (mm)	Annual water yield (mm)
Mahakali	1737664	2156	149	270	807	400	1007	1886
Karnali	4989216	2283	742	332	591	594	625	1430
Babai	332916	1631	-	-	466	643	548	949
West Rapti	625328	1857	32	32	662	702	426	1154

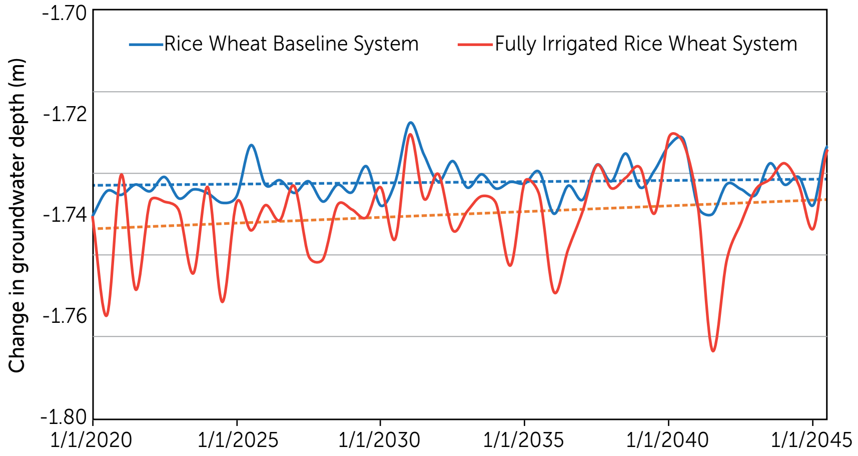


Figure 3-1. Groundwater fluctuation for the baseline scenario (rainfed rice–wheat system) and groundwater irrigated rice–wheat system) in the Mahakali watershed. The y-axis represents the change in groundwater depth from the ground surface. (note: this change in depth is indicative of the relative trend – not the actual water table fluctuation.)

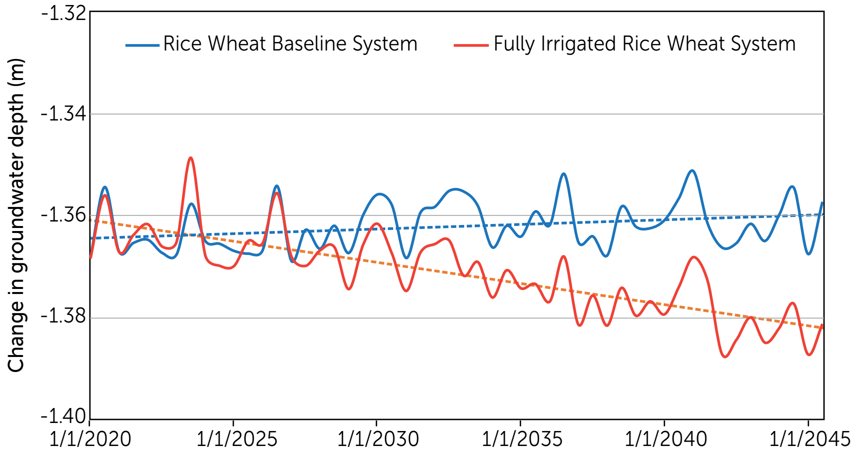


Figure 3-2. Groundwater fluctuation for the baseline scenario (rainfed rice–wheat system) and Scenario 1 (groundwater irrigated rice–wheat system) in West Rapti watershed. The y-axis represents a change in groundwater depth from the ground surface. (note: this change in depth is indicative of the relative trend – not the actual water table fluctuation.)

The average amount of groundwater recharge was increased when surface irrigation was increased due to infiltration in the Karnali watershed. When 25% of the land was provided with surface irrigation and 75% with groundwater irrigation, the average annual groundwater recharge was 311 mm/year. However, when surface and groundwater contribution was 50% each, the annual groundwater recharge increased to 367 mm per year. When the surface water contribution was 75%, the annual groundwater recharge was increased to 413 mm/year.

Rice–wheat irrigated system was sustainable for more than 89% of the currently cultivated land in the Mahakali watershed when both monsoon and dry season crops were provided with groundwater irrigation (Table 3.2.); however, in the West Rapti watershed, only 36% to 57% of the total cultivated area could be sustainably provided with groundwater irrigation (Table 3.3). This scenario would be sustainable in the Babai and West Rapti watersheds if irrigation for dry season crops was

Table 3-2. Comparison of annual irrigation water requirement and annual groundwater recharge for the rice–wheat (baseline) system and rice–wheat (fully irrigated) system in the Mahakali watershed.

	Rice–wheat (baseline)				Rice–wheat (fully irrigated)			
Year	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)
2000–20	179	428	994	115	357	428	1027	92
2021–2035	179	428	1013	117	357	428	1002	89
2035–2050	179	428	1043	120	357	428	1071	96

Table 3-3. Comparison of annual irrigation water requirement and annual groundwater recharge for rice–wheat (baseline) system and in rice–wheat (fully irrigated) system in the West Rapti watershed.

	Rice–wheat (baseline)				Rice–wheat (fully-irrigated)			
Year	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)
2000–20	433	373	407	35	433	360	408	36
2021–35	333	380	545	53	333	368	536	54
2035–50	334	387	564	55	334	349	553	57

provided through groundwater, and irrigation for the monsoon season crop (that is, rice) was either provided with surface water or rainfed.

Impacts on surface water

Under the scenario of closing the yield gap in the rice–wheat system, providing sufficient surface irrigation for rice and wheat in the Tarai districts through Mahakali, Ranijamara and Rajapur irrigation projects did not have a significant impact on the total flow of snow-fed perennial rivers (for example, Mahakali and Karnali) during each season, as the change in flow was less than 5% to 8% for each season (Figure 3-3). Mahakali river, having only one-third of its draining area falling in Nepal (two-thirds in India), had annual water availability of 10,924 million m^3 at the tributaries draining Nepal; the Karnali river, having 94% of its draining area falling in Nepal (6% in Tibet), had annual water availability of 71,279 million m^3. However, the flow during the post-monsoon season in Babai river reduced by about 11% to 12%, and that in West Rapti river by about 1% to 7% after providing irrigation for rice and wheat thorough the canals of Babai, Sikta and other smaller irrigation projects in Banke, Bardiya and Dang. Water in the rain- and spring-fed rivers (such as West Rapti and Babai) was not sufficient for irrigation during pre- and post-monsoon seasons, as at least 30% of the total river discharge is left in the river for environmental flow requirements. The scenario that causes the highest reduction in the stream was cultivating vegetables between *kharif* and spring rice as the irrigation requirement for three crops in a year is higher than the single- and double-cropping systems.

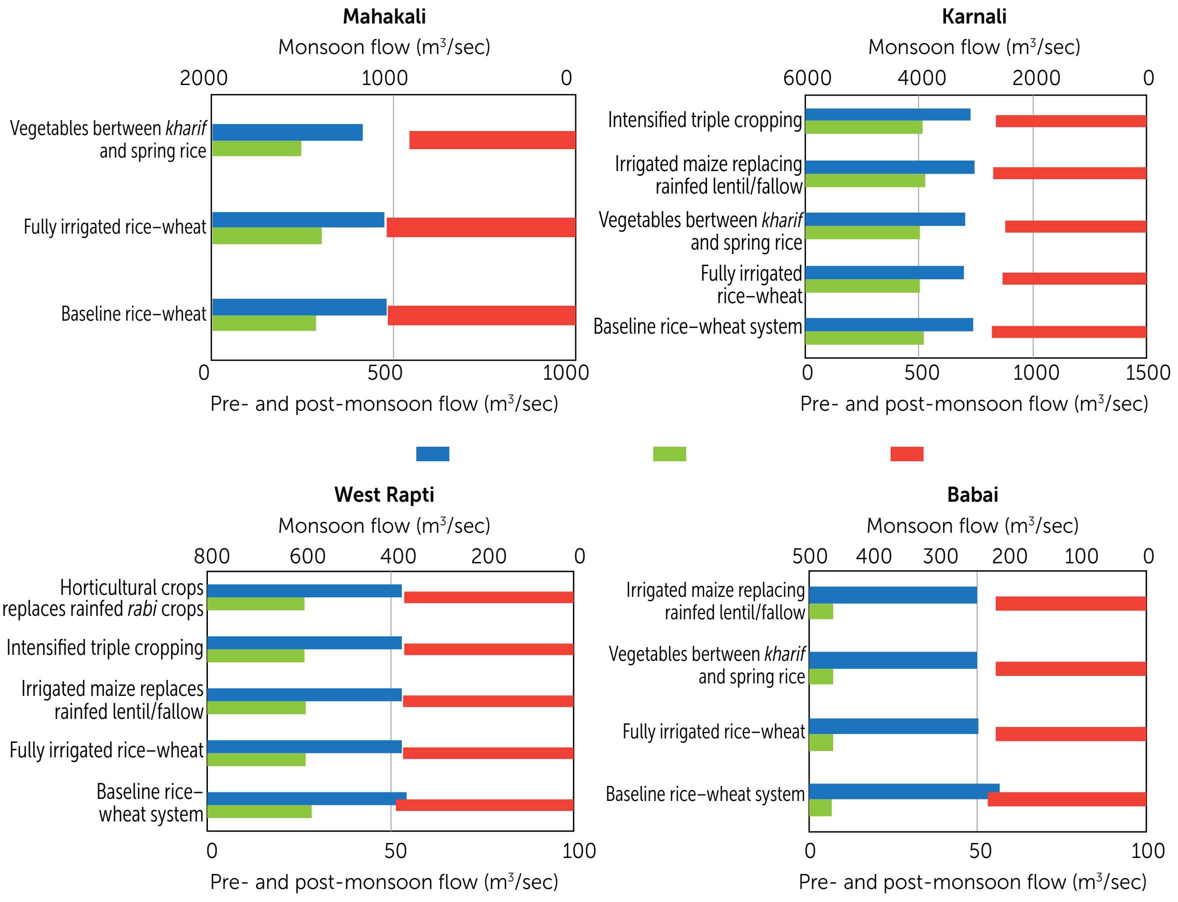


Figure 3-3. Percentage change in average seasonal streamflow before and after irrigation was supplied for different scenarios in Mahankali, Karnali, West Rapti and Babai rivers.

Impact on crop yield

The average crop yield and total crop production for different alternate scenarios were analyzed and compared with those obtained from baseline scenarios. The comparison was performed using rice equivalent yield, calculated by converting the yield of non-rice crops into equivalent rice yield based on the local price of different crops.

The average yield of rice was observed to be elevated by 17% to 80% (Figure 3-4) and the average yield of wheat by 30% to 217% (Figure 3-5) in different districts and after sufficient irrigation was provided to the crops. The increase in rice production was highest in Kailali (with an increase of around 80%, from 78613 t to 321231 t), as Kailali is one of the largest districts in the western Tarai region of Nepal, with over over 72,000 has of land under rice cultivation and thus the largest potential of irrigation expansion. The lowest increase of 17% (from 93,294 t to 109361 t) was observed in the Banke district; this was due to the lower availability of surface and groundwater resources in the region. Because of limited supply of water, only the smaller area was irrigated. However, the irrigated fields were dried quickly as the surrounding lands were not watered sufficiently.

Similarly, the highest increase in wheat production was in the Kanchanpur district (by around 217%, from 55,889 t to 177,352 t) and the lowest increase in the Dang district (29%, from 68,514 t to 94,895 t) (Figure 3-6). In Kailali district in the western Tarai region, wheat production was observed to be very favourable; here, a higher increase in wheat yield can be achieved through a sustainable irrigation system, improved seed, and adequate fertilizers, pesticides and insecticides. It was reported that farmers in these regions have been using older stock of fertilizers and seeds (Devkota and Phuyal, 2015). The Dang district observed comparatively less increase in wheat yield even after sufficient irrigation was provided, probably due to a decrease in average winter temperature based on climate change data (Devkota and Phuyal, 2015).

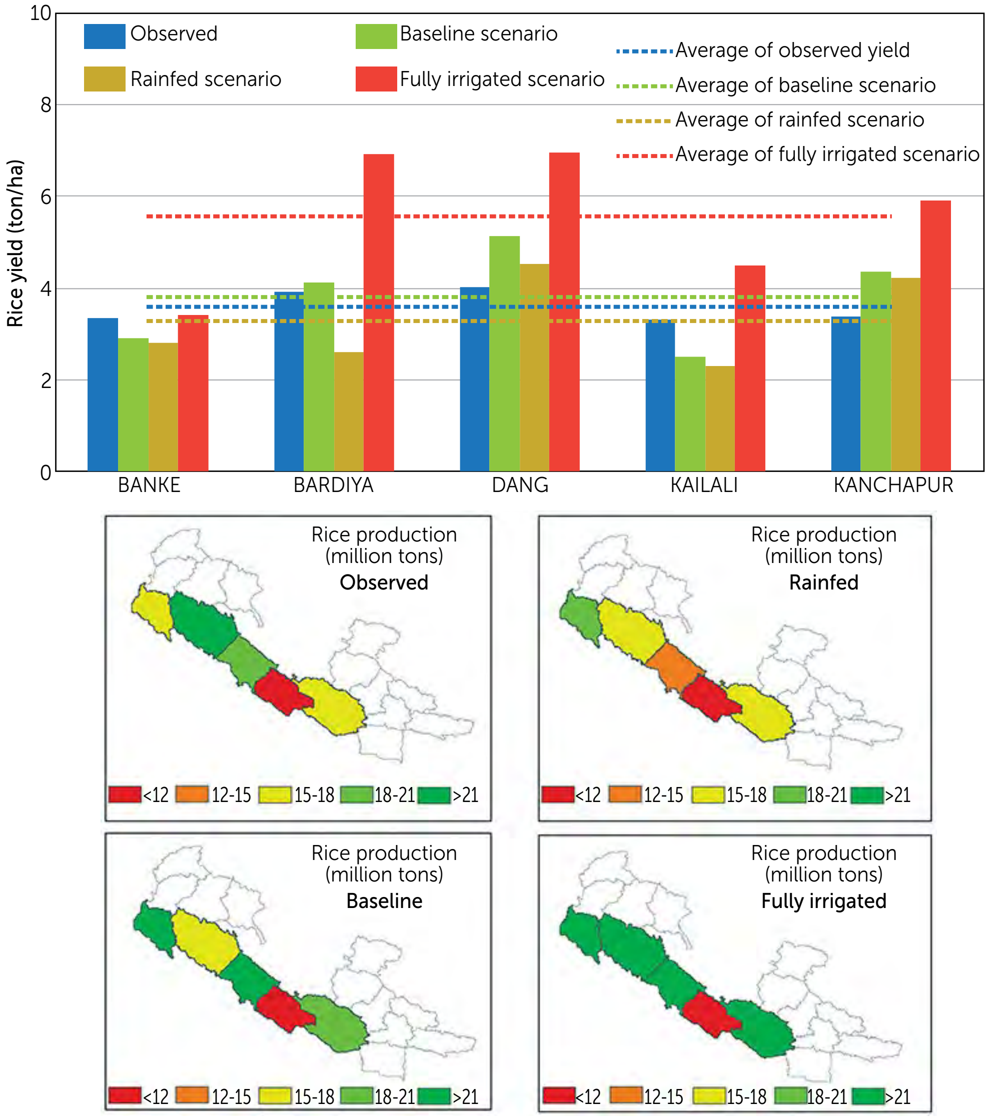
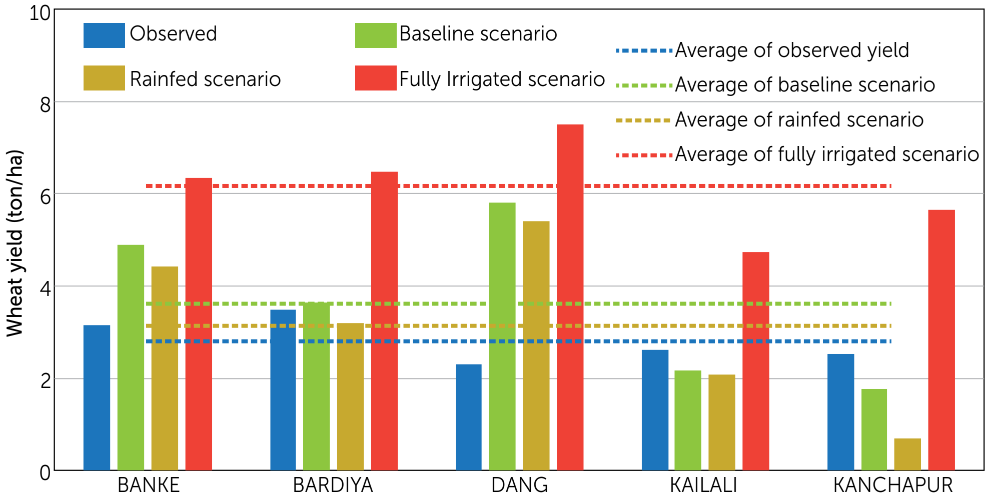


Figure 3-4. Average rice yield (upper) and total rice production (lower) for baseline and irrigation scenarios in different districts.

Scenario 2: Rice–vegetable–rice instead of rice–wheat

Impact of groundwater resource

Both the rice–wheat baseline system and the scenario of cultivating vegetables between monsoon and spring rice crops showed a very gradual amount of decline in groundwater reserve in Bardia (Karnali watershed) and Kanchanpur (Mahakali watershed) districts (Figure 3-6). For the Karnali watershed, the average declination in groundwater was 24 mm from 2020 to 2050 for the rice–wheat baseline scenario and 16 mm for the rice–vegetable–rice scenario. This suggests that the cultivation of vegetables causes less environmental cost than wheat in a rice cultivation system.



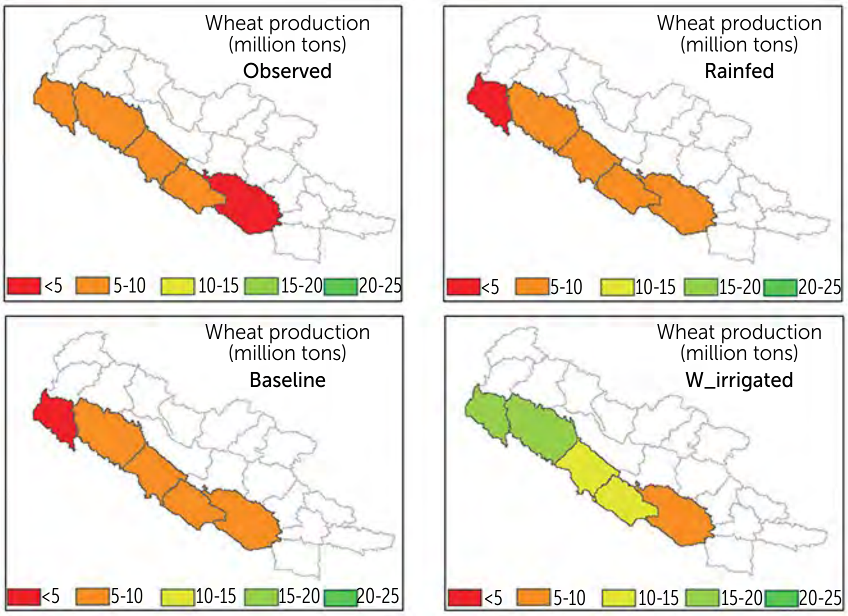


Figure 3-5. Average wheat yield (upper) and total wheat production (lower) for baseline and irrigation scenarios in different districts.

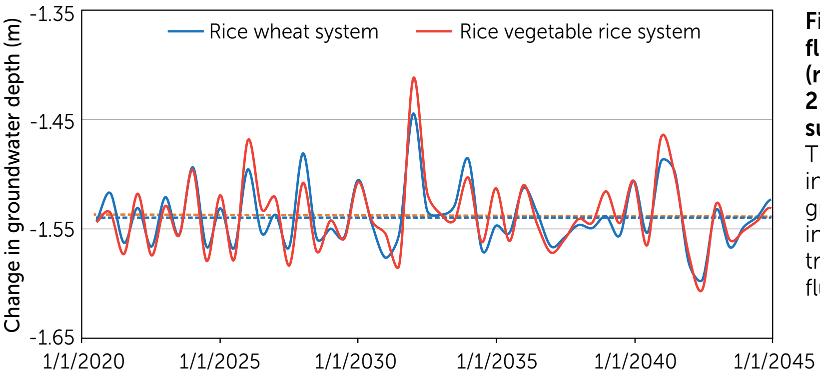


Figure 3-6. Groundwater fluctuation for baseline scenario (rice–wheat system) and Scenario 2 (rice–vegetable–rice system) in sub-basin 53 of Karnali watershed. The y-axis represents a change in groundwater depth from the ground surface.(note: this change in depth is indicative of the relative trend – not the actual water table fluctuation.)

The rice–vegetable–rice system was observed to be sustainable for 69% to 73% of land in the Mahakali watershed, although the available water resources in the Mahakali watershed were far more than what is required for the rice–wheat system (Table 3-4). Similarly, 39% to 44% of land currently cultivated in the Karnali watershed, sustainable for the rice–wheat system, was increased to 45% to 61% for the rice vegetable–rice system (Table 3-5) due to an increase in the groundwater recharge rate after irrigation was supplied during dry seasons. In the same way, 62% to 64% of currently cultivated land in the Babai watershed, sustainable for the rice–wheat system, was decreased to 48% to 52% for the rice–vegetable–rice system (Table 3-6) due to increased irrigation demand during the dry season despite the fact that the groundwater recharge rate was increased.

The annual groundwater recharge in the Mahakali watershed was higher than that of Karnali, Babai and West Rapti watersheds and thus the scenario of rice-vegetable-rice was more suitable in this watershed. The groundwater recharge was increased when vegetables were planted between two rice crops, due to surplus irrigation water supplied from the surface water system. As the annual groundwater irrigation requirement is more than groundwater recharge for all current and future periods for this scenario, it is sustainable if the groundwater is drawn only during dry periods, and monsoon season crops are supplemented by surface water.

Impacts on surface water

Under the rice–vegetable–rice scenario, the pre- and post-monsoon flow of Mahakali river was reduced by 14% and the monsoon flow by 12%, compared to -5% reduction of stream in all seasons under the rice–wheat system (Figure 3-3). This greater reduction under the rice-vegetable-rice system was because of the increased crop rotations, and in particular due to the cultivation of rice twice a year (rice consumes a great deal more water than wheat). The scenario of rice–vegetable–rice in place of rice–wheat did not impact much on the total flow of the Karnali river (which has a higher baseflow), as the change in flow ranged from 1% to 8% for all seasons, even after the extraction of

Table 3-4. Comparison of annual irrigation water requirement and annual groundwater recharge during the baseline scenario (rice–wheat system) and Scenario 2 (rice–vegetable–rice system) in the Mahakali watershed.

Year	Rice–wheat				Rice–vegetable–rice			
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation Practice (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation Practice (%)
2000–20	179	428	923	107	467	626	944	69
2021–35	179	428	942	109	467	626	991	72
2035-50	179	428	985	114	467	626	1000	73

Table 3-5. Comparison of annual irrigation water requirement and annual groundwater recharge during the baseline scenario (rice–wheat) and Scenario 2 (rice–vegetable–rice) in the Karnali watershed.

Year	Rice–wheat				Rice–vegetable–rice			
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation practice land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation practice land (%)
2000–20	355	467	452	39	606	467	692	45
2021–35	357	400	475	44	536	400	822	61
2035–50	498	458	489	36	607	458	711	47

Table 3-6. Comparison of annual irrigation water requirement and annual groundwater recharge during baseline scenario (rice–wheat) and Scenario 2 (rice–vegetable–rice) in Babai watershed.

Year	Rice–wheat				Rice–vegetable–rice			
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation practice land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation practice land (%)
2000–20	278	319	547	64	580	319	620	48
2021–35	318	312	576	64	572	312	650	51
2035–50	307	332	564	62	551	332	657	52

sufficient irrigation water through the Ranijamara and Rajapur irrigation projects. The scenario causing the highest reduction in the stream was the rice-vegetable-rice this was due to the cultivation of an extra crop a year and because rice consumes a greater amount of water than other crops. However, when the scenarios model a reduction in the flow of the Babai river (which has a lower baseflow) by about 11% to 12% during the post-monsoon season, sufficient water may not be available for surface irrigation from the Babai irrigation project in Bardiya and smaller irrigation projects in Dang, as 30% of the total flow must be left in the river for environmental flow requirements.

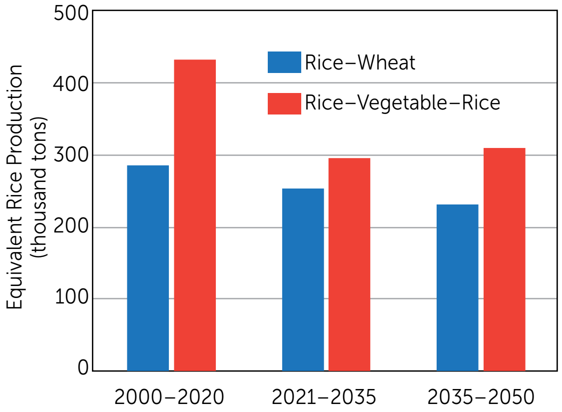


Figure 3-7. Rice equivalent production for baseline scenario (rice–wheat system) and Scenario 2 (rice–vegetable–rice system) during the current, near-future and mid-term future periods.

Impact on crop yield

The scenario showed that cultivation of rice–vegetable–rice instead of rice–wheat in Mahakali and Babai watersheds increased total rice equivalent production by 51% in the current term, with increases of 17% and 34% during the near-term future (2021–35) and mid-term future (2035–50) respectively (Figure 3-7). The increase in yield was due to additional crops grown in a year (Table 3-7) and the higher value of the vegetable crop in comparison to rice and wheat. The increase in crop yield was lower during the near and mid-term future compared to the current term, perhaps because of the temperature stress – based on climate change data, average temperature decreased although average rainfall in the future period increased.

Scenario 3: Replacing rainfed-lentil and fallow land with irrigated maize

Impact on groundwater resource

According to the scenario, the rice–irrigated maize cropping pattern had little impact on the groundwater reserve for both Kailali in the Karnali watershed and Dang in the West Rapti watershed, as the change in groundwater reserve between 2020 to 2050 was -15 mm for Kailali (Figure 3-8) and +8 mm for Dang (Figure 3-9). This suggested that from an environmental point of view, both the rice–lentil and rice–irrigated maize systems were sustainable.

Table 3-7. Average crop yield for the baseline scenario (rice–wheat system) during the current, near-future and mid-term future periods.

	Rice–wheat				Rice–vegetable–rice					
Year	Rice yield (t/ha)	Rice production (kt)	Wheat yield (t/ha)	Wheat production (kt)	Rice yield (t/ha)	Rice production (kt)	Tomato yield (t/ha)	Tomato production (kt)	Spring rice yield (t/ha)	Spring rice production (kt)
2000–20	4.2	161	2.8	107	4.2	161	1.3	49	5.3	204
2021–35	3.7	142	2.5	97	3.7	142	0.7	16	3.4	131
2035–50	3.7	142	2	77	3.8	146	0.6	15	3.7	142

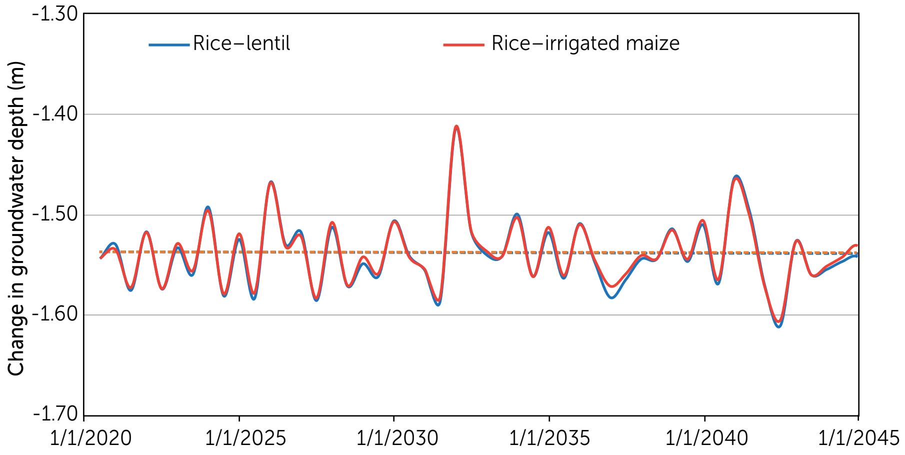


Figure 3-8. Groundwater fluctuation for the baseline scenario (rice–rainfed lentil) and Scenario 3 (rice–irrigated maize) in sub-basins 48 and 49 of Karnali watershed. The y-axis represents the change in groundwater depth from the ground surface. (note: this change in depth is indicative of the relative trend – not the actual water table fluctuation.).

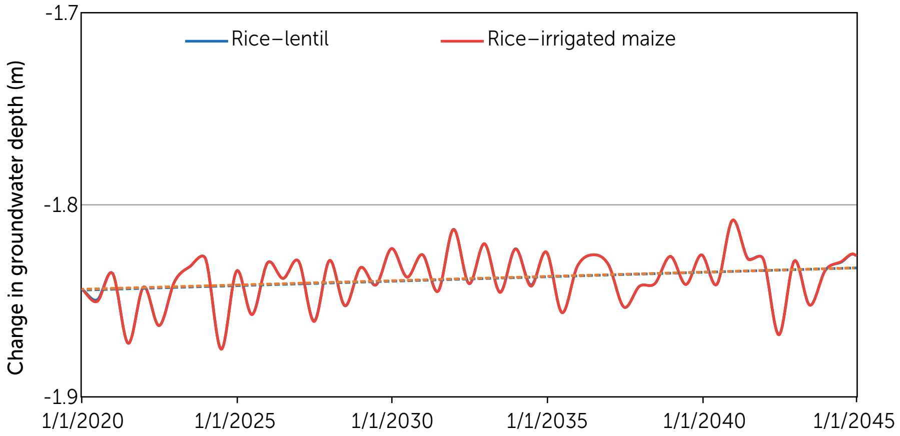


Figure 3-9. Groundwater fluctuation for the baseline scenario (rice–rainfed lentil) and Scenario 3 (rice–irrigated maize) in sub-basins 26 and 29 of West Rapti watershed. The y-axis represents the change in groundwater depth from the ground surface. (note: this change in depth is indicative of the relative trend – not the actual water table fluctuation.).

The slight increase in groundwater reserve in the long-run observed in Dang was mainly due to an increase in rainfall.

The rice-irrigated maize system was sustainable for 31% to 40% of currently cultivated land in the Karnali watershed (Table 3-8), 61% to 77% of currently cultivated land in the Babai watershed (Table 3-9) and 31% to 49% of currently cultivated land in the West Rapti watershed (Table 3-10) when the entire field was irrigated by groundwater.

Groundwater recharge decreased in the Karnali watershed after excessive groundwater water is pumped to irrigate maize during the dry season but was observed to be stable in Babai and West Rapti watersheds. This suggests that if farmers withdraw more than 70% of the annual groundwater recharge,

Table 3-8. Comparison of annual irrigation water requirement and annual groundwater recharge for rice–rainfed lentil and rice-irrigated maize in sub-basins 48 and 49 of the Karnali watershed.

Year	Rice-lentil (rainfed)				Rice-maize (irrigated)			
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)
2000–20	0	467	423	63	440	467	398	31
2021–35	0	400	529	93	416	400	411	35
2035–50	0	496	541	76	407	496	513	40

Table 3-9. Comparison of annual irrigation water requirement and annual groundwater recharge for rice–rainfed lentil and rice–irrigated maize in sub-basins 17, 18 and 21–27 of Babai watershed.

Year	Rice–lentil (rainfed)				Rice–maize (irrigated)			
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)
2000–20	0	308	612	139	454	308	664	61
2021–35	0	298	831	195	386	298	793	81
2035–50	0	330	864	183	426	330	831	77

Table 3-10. Comparison of annual irrigation water requirement and annual groundwater recharge for rice–rainfed lentil and rice–irrigated maize systems in sub-basins 26 and 29 of West Rapti watershed.

Year			Rice–lentil (rainfed)			Rice–maize (irrigated)		
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)
2000–20	0	389	330	59	372	389	332	31
2021–35	0	394	507	90	341	394	514	49
2035–50	0	399	524	92	364	399	531	49

this will further undermine the groundwater reserve and cause negative environmental externalities. Caution should therefore be taken while using groundwater for irrigation in the Karnali watershed.

Similarly, groundwater recharge increased by 8% in the Babai watershed when rainfed lentil was replaced by irrigated maize. This increase was due to the infiltration of irrigation water supplied from the surface water system. Groundwater irrigation may beracticedd sustainably for both scenarios (the rice–wheat and rice–vegetable–rice systems), when the dry season crops (wheat, vegetables and spring rice) are provided with groundwater irrigation and the monsoon season crop (*kharif* rice) supplemented with surface water irrigation. Groundwater may be preserved for dry season irrigation only when required, for example when there are rainfall variabilities such as drought and dry spells, and during periods when rainfall starts or ends late.

As lentil (cultivated in certain areas of the watershed) is mostly rainfed, rice–lentil can be implemented sustainably for the entire agricultural land (139% to 195%) using groundwater irrigation (Table 3-9). As the winter and spring seasons have short growing periods, lentil is a suitable crop to cultivate, as it requires 80 to 110 days from the day of cultivation to produce yield. Moreover, lentil has high economic value and environmental benefits such as improving soil fertility. Compared to lentil, maize required more irrigation water, leading to a reduction in agricultural land able to be cultivated using irrigation from groundwater.

Impacts on surface water

Under the scenario of rice–irrigated maize instead of a rice–lentil system, during the dry season the flow of Karnali, Babai, and West Rapti rivers reduced by 1%, 12% and 6% respectively compared to the baseline rice–wheat system (Figure 3-3). Rice–irrigated maize caused a greater reduction because of the irrigation provided to maize. However, there was little impact on the total flow of the Karnali river (which has a higher base flow) – the change in flow was about 1% – however, it impacted Babai and West Rapti rivers which have a lower baseflow. Sufficient water may not be available for surface irrigation from the Babai irrigation project in Bardiya and smaller irrigation projects in Dang, as 30% of the total flow must be left in the river for environmental flow requirements.

The average flow at the outlet of Babai and West Rapti watersheds was reduced even when only groundwater was withdrawn to irrigate rice and maize in the rice–irrigated maize scenario. This suggests that the extraction of groundwater affects the nearby streams and rivers.

Impact on crop yield

In this scenario, cultivation of rice–irrigated maize instead of rice–lentil in Karnali, Babai and West Rapti watersheds showed that total rice equivalent production decreased by 5% in the current term, 11% during the near-term future (2021–35) and 18% during mid-term future (2035–50) (Figure 3-10).

The rice equivalent yield, based on local price of crops, for the rice–irrigated maize system was lower than that for the rice–lentil system because of the higher price of lentil in comparison to maize even though the actual maize yield for was greater than lentil yield (Table 3-11). Besides their high economic value, lentil as a legume also improves soil fertility. From both economic and environmental points of view, the cultivation of maize in place of lentil and expanding the irrigation system for the cultivation of maize may not be worth it. Cultivating crops such as lentil is more beneficial than maize in the Dang district, due to the small irrigation water requirement and other environmental benefits such as improving soil fertility. Overall, the rice–lentil scenario was the best in terms of improving overall agricultural production and impacts on surface water and groundwater.

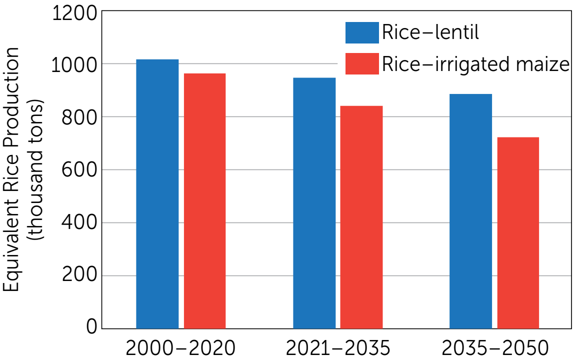


Figure 3-10. Rice equivalent production for baseline scenario (rice–rainfed lentil) and Scenario 3 (rice–irrigated maize) during current, near future and midterm future period.

Table 3-11. Crop yield and production for rice–wheat–lentil and rice–wheat–irrigated maize during the current, near future and mid-term future periods.

Year	Rice yield (t/ha)	Rice Production (kt)	Wheat yield (t/ha)	Wheat production (kt)	Lentil yield (t/ha)	Lentil production (kt)	Rice yield (t/ha)	Rice production (kt)	Wheat yield (t/ha)	Wheat production (kt)	Maize yield (t/ha)	Maize production (kt)
2000–20	4.0	307	4.3	330	1.3	100	4.0	307	4.3	330	3.9	300
2021–35	3.0	230	4.1	315	1.4	107	2.9	223	4.2	323	3.5	269
2035–50	3.1	238	3.6	276	1.3	100	3.1	238	3.6	277	2.4	180

Scenario 4: Rice–wheat–mungbean instead of rice–wheat

Impact on groundwater resource

Intensified triple cropping instead of a double-cropping system is desirable because three crops per year will produce more yield. Moreover, legume crops such as mungbean have a shorter growing period and also improve soil fertility, and are thus an appropriate third crop in the rice–wheat cropping system. In this scenario however, rice–wheat–mungbean may have a significant impact on groundwater reserve if the entire irrigation demand is supplied from a groundwater source. For both Kailali in the Karnali watershed and Banke in the West Rapti watershed, the change in groundwater reserve from 2020 to 2050 ranged from 250 mm to 264 mm in both the watersheds when the total irrigation requirement was supplied from a groundwater source (Figure 3-11). This indicates that providing all the required irrigation demand from a groundwater source alone is not sustainable. However, when groundwater was used to irrigate only mung bean and other crops (rice and wheat), supplemented by a surface water source, the groundwater draw-down was observed to be minimal.

The rice–wheat–mungbean system was sustainable for 27% (Table 3-12) of currently cultivated land in the Karnali watershed and 36% (Table 3-13) of currently cultivated land in the West Rapti watershed. However, the rice–wheat system was sustainable for 35% (Table 3-12) in the Karnali and West Rapti watersheds. For the future period, the rice–wheat–mungbean scenario may be sustainably cultivated in smaller land areas (that is, 39% to 44% of the agricultural land) compared to 53% to 56% in the rice–wheat scenario (tables 3-12 and 3-13). This may be due to an increase in rainfall and a decrease in evapotranspiration.

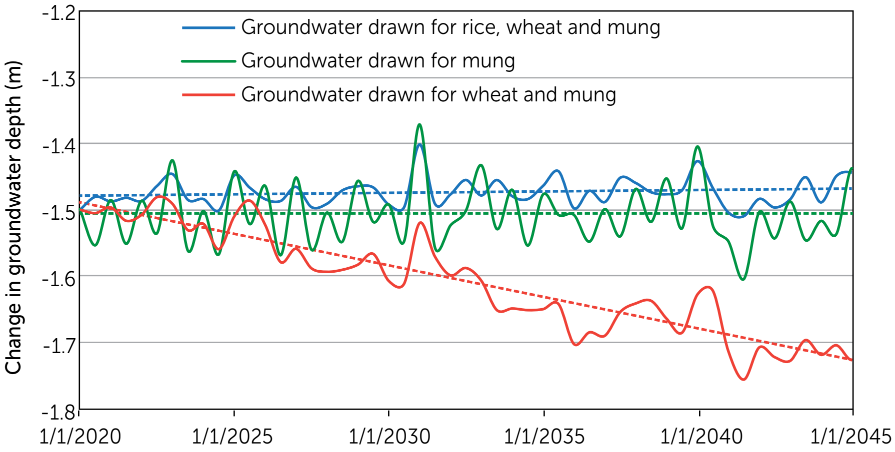


Figure 3-11. Groundwater fluctuation for rice–wheat–mungbean, wheat–mungbean, and only mungbean systems in Karnali watershed. The y-axis represents a change in groundwater depth from the ground surface. (note: this change in depth is indicative of the relative trend – not the actual water table fluctuation.).

Table 3-12. Comparison of annual irrigation water requirement and annual groundwater recharge for rice–wheat and rice–wheat–mungbean in Karnali watershed.

Year	Rice–wheat				Rice–wheat–mungbean			
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)
2000–20	354	467	406	35	640	467	429	27
2021–35	284	400	544	56	592	400	596	42
2035–50	354	458	556	48	657	458	622	39

Table 3-13. Comparison of annual irrigation water requirement and annual groundwater recharge for rice–wheat and rice–wheat–mungbean in West Rapti watershed.

Year	Rice-wheat				Rice-wheat-mungbean			
	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation of feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation of feasible land (%)
2000–20	433	373	407	35	503	376	446	36
2021–35	333	380	545	53	417	397	514	44
2035–50	334	387	564	55	451	395	534	44

Impacts on surface water

Under the rice–wheat–mungbean scenario, the flow of Karnali and West Rapti rivers during the dry season was reduced by 1% and 7% respectively compared to the baseline rice–wheat system (Figure 3-12). As both surface and groundwater were used together in this scenario, surface irrigation water was extracted from the Karnali river through Ranijamara, Rajapur and other smaller irrigation projects, and from West Rapti river through the Sikta irrigation project and other smaller irrigation projects. The slight reduction in streamflow of the river was probably due to surface water being withdrawn to irrigate crops during the dry season. Like other scenarios, this scenario also did not impact much on the total flow of the Karnali river, which has a higher baseflow, as a change in flow was about 1%, but impacted West Rapti river which has a lower baseflow. Although the Kailali district can get enough surface water from the Karnali river, sufficient surface water may not be available for irrigation in Banke, due to the lower baseflow and because 30% of the total flow must be left in the river for environmental flow requirements. The average flow of the West Rapti watersheds was observed to be reduced even when only groundwater was withdrawn to irrigate the rice–wheat–mungbean scenario, which suggests that the extraction of groundwater may affect the nearby streams and river.

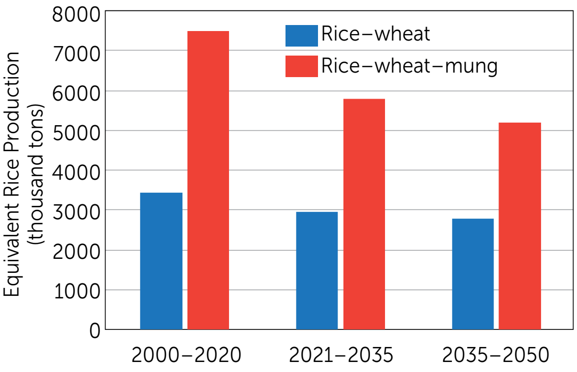


Figure 3-12. Rice equivalent production for baseline scenario (rice–wheat) and Scenario 3 (rice–irrigated maize) during current time, near future and mid-term future periods.

Impact on crop yield

In the scenario, cultivation of rice–wheat–mungbean instead of current rice–wheat in Karnali and West Rapti watersheds showed that total rice equivalent production was increased by 118% in the current term, and 96% and 87% respectively during the near-term future (2021–235) and mid-term future (2035–50) respectively (Figure 3-12). Rice equivalent yield was increased by more than 100% in the current term and by almost 100% during the future period, due to the additional crops grown in a year and the higher value of mungbean compared to rice and wheat. Mung also improves soil fertility as it is a legume crops and can fix nitrogen from the air and flourish on nitrogen-deficient soils. Thus, from both economic and environmental points of view, the cultivation of mungbean between rice and wheat by expanding the irrigation system is worth it. The reduction in crop yield and production during the near- and mid-term future compared to the current period was due to temperature stress, as the average temperature based on climate change data was observed to decrease although average rainfall was increased.

Scenario 5: A horticulture crop instead of wheat and fallow

Impact on groundwater resources

Cultivating horticultural crops in-between rice and wheat, within the 50 km radius of urban centres in the hilly and Tarai regions that have road access is desirable, as horticultural crops have high economic value and can therefore help uplift the livelihoods of the rural population. However, in the scenario, the rice–wheat–horticultural crop may have a significant impact on groundwater reserve if the entire irrigation demand is supplied from a groundwater source. For Rolpa, Argakhanchi and Dang in the West Rapti watershed, where this scenario was implemented, the change in groundwater reserve from 2020 to 2050 was 201 mm when all the irrigation requirement was supplied from a groundwater source (Figure 3-13). However, if the irrigation requirement for rice was supplemented by surface water, and groundwater preserved for wheat and potato, the decline in the groundwater reserve was reduced to 127 mm. This indicated that providing all the required irrigation demand by groundwater source alone is not sustainable.

Table 3-14. Crop yield and production for baseline (rice–wheat system) and rice–wheat–mungbean scenarios during the current, near future and mid-term future periods.

Year	Rice–wheat				Rice–wheat–mungbean					
	Rice yield (t/ha)	Rice production (kt)	Wheat yield (t/ha)	Wheat production (kt)	Rice yield (t/ha)	Rice production (kt)	Wheat yield (t/ha)	Wheat production (kt)	Mung yield (t/ha)	Mung production (kt)
2000–20	4.0	1587	4.3	1706	4.0	1587	4.7	1706	2.9	1151
2021–35	3.0	1190	4.1	1627	3.0	1190	2.5	1627	2	797
2035–50	3.1	1230	3.6	1429	3.1	1230	2.1	1429	1.7	674

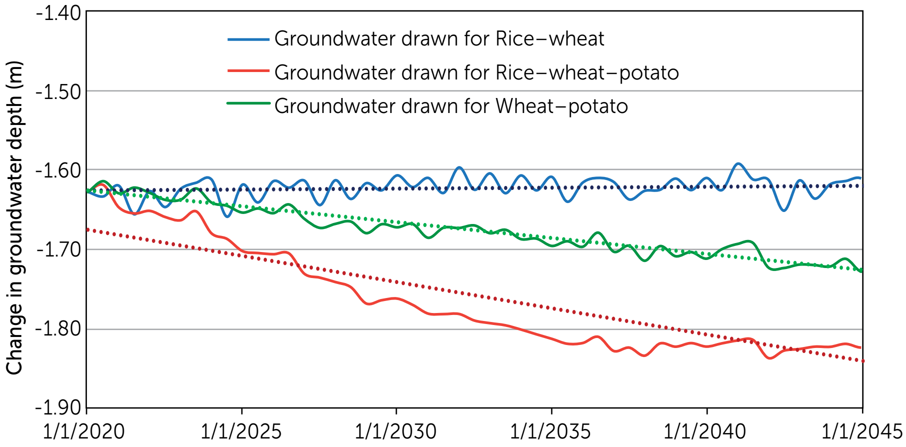


Figure 3-13. Groundwater fluctuation for the Rice–wheat (baseline), Rice–wheat–potato and Wheat–potato systems in the West Rapti watershed. (note: this change in depth is indicative of the relative, not the actual water table fluctuation).

The rice–wheat–horticultural cropping system was observed to be sustainable for 33% (Table 3-15) of currently cultivated land in the West Rapti watershed, while the rice–wheat system was sustainable for 41% (Table 3-15) of total cultivated land in West Rapti watershed. This decrease in the land that can be sustainably fulfilled by groundwater alone may be due to the additional amount of water required for the third crop. However, for the future period, the rice–wheat–potato scenario may be sustainably cultivated in 43% to 46% of the agricultural land compared to 60% to 62% in the rice–wheat scenario (Table 3-15) probably due to an increase in rainfall and decrease in evapotranspiration.

Impacts on surface water

Although the total flow of the West Rapti river decreased by 5% because of the rice–wheat–potato scenario, seasonal flow change was up to 7% (Figure 3-3). Both surface water and groundwater were conjunctively used in this scenario, surface irrigation water was used as supplementary irrigation for rice during monsoon while groundwater was used for wheat and potato in the dry season. The average flow of West Rapti watersheds was observed to be reduced even when only groundwater was withdrawn to irrigate wheat and potato in the dry season, suggesting that the extraction of groundwater may affect the nearby streams and rivers.

Impact on crop yield

In this scenario, the cultivation of horticulture crops (for example, potato) in urban hilly and Tarai sub-basins of West Rapti watersheds showed that total rice equivalent production was increased by 61% in the current term. The increase in rice equivalent production was 65% and 35% during the near-term future (2021–35) and mid-term future (2035–50) respectively. The rice equivalent yield increased due to the higher price of potato grown in fallow land. The cultivation of a horticultural crop in rice

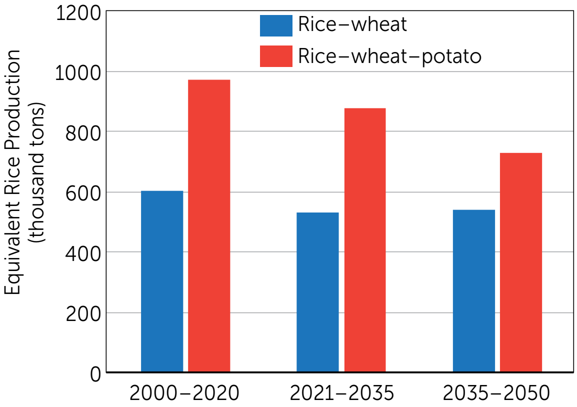


Figure 3-14. Rice equivalent production for baseline scenario (maize) and Scenario 5 (maize–potato) during the current time, near future and mid-term future.

Table 3-15. Annual irrigation water requirement and annual groundwater recharge during the rice–wheat system in the West Rapti watershed.

Year	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	Rice–wheat		Rice–horticultural crop			
			GW recharge (mm)	GW irrigation feasible land (%)	Irrigation (winter) (mm)	Irrigation (monsoon) (mm)	GW recharge (mm)	GW irrigation feasible land (%)
2000–20	218	359	336	41	336	359	326	33
2021–35	218	386	514	60	367	386	465	43
2035–50	218	383	530	62	366	383	489	46

and wheat systems by expanding efficient irrigation systems (a drip or sprinkler system) is therefore worthwhile from an economic point of view. The reduction in crop yield and production during the near- and mid-term future compared to the current period was due to temperature stress, as average temperature based on climate change data was observed to decrease although average rainfall was increased.

Assumptions and limitations

As the data used for the modeling and scenario analysis were obtained mainly from survey reports and expert opinions, they may not have captured all the spatial variation. Although SWAT can handle biophysical data effectively, not all the socio-economic data related to the cropping system obtained for this study through surveys and workshops, could be used in the SWAT modeling exercise. Rather, most of the data related to cropping and management were based on expert opinion (personal communication). As the surface/groundwater in SWAT interacted only through streams, the simulation of groundwater flow may not be 100% accurate. Moreover, for the climate change analysis only one climate model was used, and data from just one climate model may contain higher uncertainty. Similarly, for the simulation of groundwater fluctuation, as the initial condition of the groundwater level before simulation was not known, the initial groundwater depth was assumed. The simulation result may also have been affected by the uncertainty in input biophysical data such as land use, soil and weather. Similarly, observation data such as streamflow, used for hydrologic calibration of the model, may be subjected to measurement uncertainties. For example, streamflow observations are derived from rating curves which convert river stage measurements to discharge. Due to this, not only are random and systematic stage measurement errors propagated but uncertainties involved in the calibration of the rating curve are also added. Government statistics on district-wise yield and production of different crops contain a lot of uncertainty. Model calibration done using these data may lead to simulations far from reality. Moreover, there are some uncertainties in the model such as parameterizations and oversimplifications of real-world phenomena.

Table 3-16. Crop yield for baseline (rainfed corn) during current, near future and mid-term future.

Year	Rice–wheat				Rice–potato			
	Rice yield (t/ha)	Rice production (kt)	Wheat yield (t/ha)	Wheat production (kt)	Rice yield (t/ha)	Rice production (kt)	Potato yield (t/ha)	Potato production (kt)
2000–20	2.5	248	3.3	327	3.4	337	3.18	315
2021–35	2.1	208	3	297	3	297	2.9	287
2035–50	2.2	218	3	297	3	297	2.2	218

4. Conclusion

Modeling techniques were used in this study to evaluate different hypotheses on the application of cropping and management interventions, and to suggest suitable interventions for sustainable use of surface/groundwater extraction and consequent improvement in crop productivity. The scenarios were (1) closing the yield gap in the rice–wheat system, (2) cultivating vegetables between the *kharif* and spring rice, (3) replacing rainfed lentil and fallow with irrigated maize, (4) using an intensified triple-cropping instead of double-cropping system, and (5) replacing rainfed *rabi* crops with horticultural crops. These were developed based on stakeholder engagement meetings and implemented to analyze the sustainability of water resources and crop production. Simulation results showed that scaling irrigation together with various agricultural intensification and diversification scenarios can substantially contribute to increasing crop production.

The scenario, closing the yield gap in the rice–wheat system through a fully irrigated system, enhanced rice yield by 17% to 80% and wheat yield by 21% to 118%. It was sustainable in the Mahakali and Karnali watersheds when 50% of the irrigation requirement was supplemented through a surface source (irrigation canals) and 50% through a groundwater source. It showed that neither surface nor groundwater sources can provide full, year-round irrigation for the rice–wheat system across these two watersheds without causing negative environmental externalities. Although Karnali and Mahakali rivers (which are snow-fed, perennial rivers) had sufficient year-round water, West Rapti and Babai rivers (rain- and spring-fed rivers) did not have sufficient water for surface irrigation during the pre- and post-monsoon seasons. In these watersheds therefore, groundwater sources must be used to irrigate a large part of suitable land irrigation. However, if groundwater was extracted during the monsoon, water may not be available for the dry season. The monsoon season crops, such as rice, generally require irrigation only during times of the year when there is reduced rainfall or the monsoon starts late. Groundwater was therefore observed to be sustainable only if it was extracted mostly during the dry season for irrigation; monsoon crops were supplemented mostly by surface water sources and groundwater only when required.

In the second scenario, cultivating rice–vegetable–rice instead of rice–wheat increased total rice equivalent production by 51% in the current term (2000–21), 17% during the near-term future (2021–2035) and 34% during the mid-term future (2035–50). The increase in crop yield was lower during the near and mid-term future compared to the current term was perhaps because of the temperature stress, as average temperature, based on climate change data, was decreased although average rainfall in the future period was increased.

Groundwater irrigation was sustainable for the scenario rice–vegetable–rice system instead of the rice–wheat system only when the dry season crop (namely, vegetable and spring rice) was provided with groundwater irrigation and the monsoon season crop (namely, monsoon rice) was supplemented with surface water irrigation. This is because triple crop cultivation in a year consumes a significant amount of water. If all the irrigation requirements need to be fulfilled by a groundwater source alone, only 48% to 52% of the total land in the Babai watershed, 63% of cultivated land in the Mahakali watershed, and 45% to 61% of cultivated land in the Karnali watershed can be provided with groundwater sustainably.

The available water resources in the watersheds were far more than required for a rice–lentil system, as 139% to 195% of the total land can be provided with groundwater irrigation sustainably. Lentil requires a small amount of water to reach maturity and is cultivated mostly as a rainfed spring crop. Moreover, lentil has a high economic value and environmental benefits such as improving soil fertility, suggesting the rice–lentil system the most sustainable system studied in the watershed. On other hand, groundwater irrigation was sustainable for the rice–irrigated maize system when the maize was provided with groundwater irrigation and the rice was provided with surface water irrigation when required (for example, during dry spells, drought, and when the monsoon comes late). If the irrigation for both maize and rice must be fulfilled by groundwater alone, only 61% to 81% of the total land can be provided with groundwater sustainably.

Intensified triple cropping instead of a double-cropping system have a significant impact on groundwater reserve if entire irrigation demand must be supplied from groundwater source as this scenario was sustainable on only 27% to 36% of currently cultivated land. For the future period, the rice–wheat–mungbean scenario may be sustainably cultivated in smaller land areas (that is, 39% to 44% of the agricultural land) compared to 53% to 56% in the rice–wheat scenario and this may be possibly due to the increase in rainfall and decrease in evapotranspiration during future. As mungbean has several advantages (such as having a shorter growing period and potential of improving soil fertility), it is the most suitable third crop in the rice–wheat cropping system, and expanding irrigation services for the expansion of this scenario to the larger area therefore seems worthwhile.

Cultivation of horticultural crops with the rice–wheat system in sub-basins located in urban centres in hilly and Terai regions with road access can provide a significant return to farmers' investment due to their larger revenue and relatively small land footprint. According to the scenario however, the rice–wheat–horticultural crop may have a significant impact on groundwater reserve if the entire irrigation demand is supplied from a groundwater source. The change in groundwater reserve from 2020 to 2050 was 201 mm when the irrigation requirement was entirely supplied from groundwater source. However, when irrigation for rice was supplemented with surface water, the decline in groundwater reserve was reduced to 127 mm. This indicates that providing all the required irrigation demand from groundwater alone is not sustainable.

The groundwater recharge was observed to increase after irrigation due to the infiltration of irrigation water supplied from surface water sources. Although groundwater recharge may be sufficient to support large scale irrigation use, drops in the groundwater table in the dry season (even if fully recharged during the monsoon) may cause negative socio-ecological externalities such as impacting farmers’ ability to pump water, household access to water for domestic purposes, ecological needs for forests, and wildlife.

Overall, this study found that relying entirely on groundwater to improve agricultural production in Nepal may not be sustainable. The irrigation system should integrate both surface water and groundwater. In fact, in some watersheds integrating both surface and groundwater might not meet the irrigation water demand in all the agricultural land. In these cases, farmers may need to reduce the agricultural land to be irrigated to produce crops sustainably. Moreover, farmers may need to implement best management practices (such as terraces, bunds and afforestation) which help to enhance groundwater recharge and thereby provide more water for irrigation. Farmers may also need to consider cultivating water-efficient crops (such as lentil, tomato and mung, which reach maturity within short periods) to improve water productivity and yield. Cultivation of such crops helps with double or triple cultivation, thereby avoiding temperature stress periods.

5. References

Devkota, N., Phuyal, R.K., 2015. Climatic impact on wheat production in Terai of Nepal. J. Dev. Adm. Stud. 23, 1–22.

Gleeson, T., Cuthbert, M., Ferguson, G., Perrone, D., 2020. Global groundwater sustainability, resources, and systems in the Anthropocene. Annu. Rev. Earth Planet. Sci. 48, 431–463.

Government of Nepal, 2011. WATER RESOURCES OF NEPAL IN THE CONTEXT OF CLIMATE CHANGE.

IMP, 2019. Irrigation Master Plan Preparation through Integrated River Basin Planning, 2019; Prepared for Water Resources Project Preparatory Facility Department of Irrigation Ministry of Irrigation Nepal.

Krupnik, T.J., Timsina, J., Devkota, K.P., Tripathi, B.P., Karki, T.B., Urfels, A., Gaihre, Y.K., Choudhary, D., Beshir, A.R., Pandey, V.P., Brown, B., Gartaula, H., Shahrin, S., Ghimire, Y.N., 2021. Chapter Four - Agronomic, socio-economic, and environmental challenges and opportunities in Nepal's cereal-based farming systems, in: Sparks, D.L.B.T.-A. in A. (Ed.), . Academic Press, pp. 155–287. https://doi.org/ https://doi.org/10.1016/bs.agron.2021.06.004.

Lopez, J.R., Winter, J.M., Elliott, J., Ruane, A.C., Porter, C., Hoogenboom, G., Anderson, M., Hain, C., 2022. Sustainable Use of Groundwater May Dramatically Reduce Irrigated Production of Maize, Soybean, and Wheat. Earth's Futur. 10, e2021EF002018.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900.

Nepal, S., Neupane, N., Belbase, D., Pandey, V.P., Mukherji, A., 2021. Achieving water security in Nepal through unravelling the water-energy-agriculture nexus. Int. J. Water Resour. Dev. 37, 67–93.

Pandey, V.P., Ray, A., Khadka, M., 2021. Towards Conjunctive Use of Surface Water and Groundwater Resources as a Response to Water Access Challenges in the Western Plains of Nepal.

Ratha, D.K., De, S., Schuettler, K., Seshan, G.K., Yameogo, N.D., 2018. Migration and remittances: recent developments and outlook-transit migration.

Sharma, K.C., 2001. Crop diversification in Nepal. Crop Diversif. Asia-Pacific Reg. 81.

Shrestha, N., Raes, D., Sah, S.K., 2013. Strategies to improve cereal production in the Terai region (Nepal) during dry season: simulations with aquacrop. Procedia Environ. Sci. 19, 767–775.

Shrestha, S.R., Tripathi, G.N., Laudari, D., 2018. Groundwater resources of Nepal: An overview. Groundw. South Asia 169–193.

Subedi, S., Ghimire, Y.N., Devkota, D., Kharel, M., Gautam, S., Sharma, B., Sapkota, B.K., 2020. Socio-economics of wheat production in Kailali and Sunsari districts of Nepal. J. Agric. Nat. Resour. 3, 29–37.

Thapa, B., Scott, C.A., 2019. Institutional strategies for adaptation to water stress in farmer-managed irrigation systems of Nepal. Int. J. Commons 13.

WEPA, 2021. Water Environment Partnership in Asia [WWW Document]. URL http://www.wepa-db.net/policies/state/nepal/state.htm.

World Bank, 2021. Data Bank: World Development Indicators [WWW Document]. URL https://databank.worldbank.org/source/world-development-indicators.

Hu, J., Ma, J., Nie, C., Xue, L., Zhang, Y., Ni, F., Deng, Y., Liu, J., Zhou, D., Li, L., Wang, Z., 2020. Attribution Analysis of Runoff Change in Min-Tuo River Basin based on SWAT model simulations, China. Sci. Rep. 10, 2900. https://doi.org/10.1038/s41598-020-59659-z.

Kim, J., Lee, J., Park, J., Kim, Sehoon, Kim, Seongjoon, 2021. Improvement of Downstream Flow by Modifying SWAT Reservoir Operation Considering Irrigation Water and Environmental Flow from Agricultural Reservoirs in South Korea. Water 13, 2543.

Li, C., Fang, H., 2021. Assessment of climate change impacts on the streamflow for the Mun River in the Mekong Basin, Southeast Asia: Using SWAT model. CATENA 201, 105199.

Sahar, A.A., Hassan, M.A., Abd Jasim, A., 2021. Estimating the Volume of Sediments and Assessing the Water Balance of the Badra Basin, Eastern Iraq, Using Swat Model and Remote Sensing Data. Iraqi Geol. J. 88–99.

Schmidt, E., Zemadim, B., 2013. Hydrological modelling of sustainable land management interventions in the Mizewa watershed of the Blue Nile basin. International Livestock Research Institute.

Strohmeier, S., 2019. Soil and Water Assessment Tool (SWAT): modeling catchment to basin scale hydrology and agricultural management scenarios.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W., 2012. SWAT: Model use, calibration, and validation. Trans. ASABE 55, 1491–1508.

Bhatta, B., Shrestha, S., Shrestha, P.K., Talchabhadel, R., 2019. Evaluation and application of a SWAT model to assess the climate change impact on the hydrology of the Himalayan River Basin. Catena 181, 104082.

Dhaubanjar, S., Prasad Pandey, V., Bharati, L., 2020. Climate futures for Western Nepal based on regional climate models in the CORDEX-SA. Int. J. Climatol. 40, 2201–2225.

Draper, N.R., Smith, H., 1966. Applied regression analysis, New York, 1966. EM Pugh GH Winslow, Anal. Phys. Meas. Addison-Wesley, New York 26.

ESGF, 2021. The Earth System Grid Federation [WWW Document]. URL https://esgf-node.llnl.gov/search/esgf-llnl/.

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., 2014. Evaluation of climate models, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 741–866.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci Data. 2015; 2: 150066.

Gonzalez, P., Neilson, R.P., Lenihan, J.M., Drapek, R.J., 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Glob. Ecol. Biogeogr. 19, 755–768. https://doi.org/https://doi.org/10.1111/j.1466-8238.2010.00558.x

ICIMOD, 2010. Land Cover of Nepal 2010 [WWW Document]. Int. Cent. Integr. Mt. Dev. (ICIMOD), Kathmandu, Nepal. URL http://rds.icimod.org/Home/DataDetail?metadataId=9224.

IMP, 2019. Irrigation Master Plan Preparation through Integrated River Basin Planning, 2019; Prepared for Water Resources Project Preparatory Facility Department of Irrigation Ministry of Irrigation Nepal.

ISRIC, 2021. International Soil Reference and Information Centre(ISRIC) Soil Data Hub [WWW Document]. URL https://www.isric.org/explore/isric-soil-data-hub.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900.

Nash, J.E., Sutcliffe, J. V, 1970. River flow forecasting through conceptual models part I—A discussion of principles. J. Hydrol. 10, 282–290.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2005. Soil and water assessment tool theoretical documentation, version 2005. Temple, Tex.: USDA-ARS Grassland. Soil Water Res. Lab. 8.

Pandey, V.P., Ray, A., Khadka, M., 2021. Towards Conjunctive Use of Surface Water and Groundwater Resources as a Response to Water Access Challenges in the Western Plains of Nepal.

Pathak, D., 2018. Status of groundwater exploitation and investigation in Terai and Inner Teri region of Nepal. Bull. Nepal Hydrogeol. Assoc. 3, 77–83.

Rathjens, H., Bieger, K., Srinivasan, R., Chaubey, I., Arnold, J.G., 2016. CMhyd user manual. Doc. Prep. Simulated Clim. Chang. Data Hydrol. Impact Study.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70, 1569–1578.

SRTM, 2021. Shuttle Radar Topography Mission.

Urfels, A., McDonald, A.J., Krupnik, T.J., van Oel, P.R., 2020. Drivers of groundwater utilization in water-limited rice production systems in Nepal. Water Int. 45, 39–59.

USGS, 2021. United States Geological Survey, Global Visualization (GLOVIS) portal [WWW Document]. URL http://earthexplorer.usgs.gov/.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., 2011. The representative concentration pathways: an overview. Clim. Change 109, 5–31.

Wu, K., Johnston, C.A., 2007. Hydrologic response to climatic variability in a Great Lakes Watershed: A case study with the SWAT model. J. Hydrol. 337, 187–199. https://doi.org/ https://doi.org/10.1016/j.jhydrol.2007.01.030.

ANNEX A: INPUT DATA SOURCES USED FOR WATERSHED ANALYSIS

Table A1. List of geospatial data sources used for watershed analysis

Geospatial data	Source	Analysis and/or processing	Data use
Digital elevation model (DEM) (30 m)	USGS 3DEP		Watershed delineation
Land use and land cover (LULC) (30 m)	ICIMOD	Merged with crop mask layers to form LULC map for modeling	HRU delineation
Crop mask layers	CIMMYT	Merged with crop mask layers to form LULC map for modeling	Crop mask layers provide detailed crop-wise land use categories for agricultural lands
Global soil grid (1 km)	ISRIC	Soil database prepared using the Pedotransfer function (Saxton and Rawls, 2006) and appended to a SWAT database	HRU delineation and land management input to SWAT
Weather data (precipitation, maximum/minimum temperatures, relative humidity, solar radiation and wind speed)	DHM, Kathmandu	Data extracted in the SWAT input format	Application in ArcSWAT
Hydrologic data	DHM, Kathmandu	Data extracted in the SWAT–CUP input format	Streamflow calibration
Groundwater depth	Survey	Data analyzed before comparing with SWAT output	Groundwater depth calibration
Cropping and management operation	(CSISA) Survey and expert opinion	Data analyzed and input manually in the SWAT model	Model development

ANNEX B: SWAT PARAMETERS USED FOR THE CALIBRATION OF STREAMFLOW

Table B-1. SWAT parameters used for the calibration of streamflow at Karkalegaon (gauging station: 120) located near sub-basin 10, Mahakali river watershed

	Parameter	Description	Unit	Calibrated value	Minimum value	Maximum value
1	R_CN2.mgt	CN2 SCS runoff curve number for moisture		-0.025575	-0.1	0.1
2	V_CANMX.hru	Maximum canopy storage mm Runoff	mm	10.0825	5	15
3	V_PLAPS.sub	Precipitation lapse rate	mm.km^{-1}	503.975006	0	600
4	V_TLAPS.sub	Temperature lapse rate	°C.km^{-1}	-6.695	-8	-4
5	V_ALPHA_BF.gw	Baseflow recession constant days Groundwater	day $^{-1}$	0.099257	0.001	0.1
6	V_ALPHA_BF_D.gw	Alpha factor for groundwater recession curve of the deep aquifer	day $^{-1}$	0.875625	0.75	1
7	A_GW_DELAY.gw	Groundwater delay time	day	65.700005	-30	90
8	A_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	mm	-785	-1000	1000
9	A_REVAPMN.gw	Threshold depth of water in the shallow aquifer for. “revap” or percolation to the deep aquifer to occur	mm	-93.75	-750	750
10	V_GW_REVAP.gw	Groundwater "revap" coefficient.		0.041225	0.02	0.05
11	R_SOL_AWC(..).sol	Available water capacity of the soil layer	mm/mm soil	0.043575	-0.05	0.05
12	V_ESCO.hru	Soil evaporation compensation factor		0.911025	0.9	0.95
13	V_SFTMP.bsn	Snowfall temperature	°C	-0.632125	-2	3
14	V_SMTMP.bsn	Snowmelt base temperature	°C	0.120425	-1	2
15	V_SMFMX.bsn	Maximum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	3.49175	2.5	4.5
16	V_SMFMN.bsn	Minimum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	0.58505	0	2.5
17	V_TIMP.bsn	Snowpack temperature lag factor		0.33375	0	1
18	V_SLSOIL.hru	Slope length for lateral subsurface flow	m	130.875	0	150
19	V_LAT_TTIME.hru	Lateral flow travel time	days	13.312501	0	15

Table B-2. SWAT parameters used for hydrologic calibration at Chisapani station (gauging station: 280) located near sub-basin 43 of the Karnali watershed.

	Parameter	Description	Unit	Calibrated value	Minimum value	Maximum value
1	R_CN2.mgt	CN2 SCS runoff curve number for moisture		0.0965	-0.1	0.1
2	V_CANMX.hru	Maximum canopy storage mm Runoff	mm	11.525001	5	15
3	V_PLAPS.sub	Precipitation lapse rate	mm.km^{-1}	173	-200	200
4	V_TLAPS.sub	Temperature lapse rate	°C.km^{-1}	-5.47	-8	-4
5	V_ALPHA_BF.gw	Baseflow recession constant days Groundwater	day $^{-1}$	0.01175	0	0.1
6	V_ALPHA_BF_D.gw	Alpha factor for groundwater recession curve of the deep aquifer	day $^{-1}$	0.8375	0	1
7	A_GW_DELAY.gw	Groundwater delay time	day	39.300003	-30	90
8	A_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	mm	-585	-1000	1000
9	A_REVAPMN.gw	Threshold depth of water in the shallow aquifer for. “revap” or percolation to the deep aquifer to occur	mm	528.75	-750	750
10	V_GW_REVAP.gw	Groundwater "revap" coefficient.		0.0454	0.02	0.1
11	R_SOL_AWC(..).sol	Available water capacity of the soil layer	mm/mm soil	0.03175	-0.05	0.05
12	V_ESCO.hru	Soil evaporation compensation factor		0.87125	0.85	0.95
13	V_SFTMP.bsn	Snowfall temperature	°C	2.6375	-2	3
14	V_SMTMP.bsn	Snowmelt base temperature	°C	0.1925	-1	2
15	V_SMFMX.bsn	Maximum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	3.745	2.5	4.5
16	V_SMFMN.bsn	Minimum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	1.69375	0	2.5
17	V_TIMP.bsn	Snowpack temperature lag factor		0.5325	0	1
18	V_SLSOIL.hru	Slope length for lateral subsurface flow	m	96.375	0	150
19	V_LAT_TTIME.hru	Lateral flow travel time	days	6.1875	0	15

Table B-3. SWAT Parameters used for hydrologic calibration at Chepang station (gauging station: 290) located near sub-basin 11 of the Babai watershed.

	Parameter	Description	Unit	Calibrated Value	Minimum value	Maximum value
1	R_CN2.mgt	CN2 SCS runoff curve number for moisture		-0.08	-0.10	0.10
2	V_CANMX.hru	Maximum canopy storage mm Runoff	mm	7.92	5.00	15.00
3	V_ALPHA_BF.gw	Baseflow recession constant days Groundwater	day $^{-1}$	0.09	0.00	0.10
4	V_ALPHA_BF_D.gw	Alpha factor for groundwater recession curve of the deep aquifer	day $^{-1}$	0.46	0.00	1.00
5	A_GW_DELAY.gw	Groundwater delay time	day	6.63	-30.00	90.00
6	A_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	mm	104.50	-1000.00	1000.00
7	A_REVAPMN.gw	Threshold depth of water in the shallow aquifer for. "revap" or percolation to the deep aquifer to occur	mm	474.38	-750.00	750.00
8	V_GW_REVAP.gw	Groundwater "revap" coefficient		0.06	0.02	0.10
9	R_SOL_AWC(..).sol	Available water capacity of the soil layer	mm/mm soil	0.00	-0.05	0.05
10	V_ESCO.hru	Soil evaporation compensation factor		0.93	0.85	0.95
11	V_SFTMP.bsn	Snowfall temperature	°C	1.05	-2.00	3.00
12	V_SMTMP.bsn	Snowmelt base temperature	°C	0.41	-1.00	2.00
13	V_SMFMX.bsn	Maximum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	3.04	2.50	4.50
14	V_SMFMN.bsn	Minimum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	1.40	0.00	2.50

Table B-4: SWAT parameters used for hydrologic calibration at Jalkundi Station (gauging station: 360) located near sub-basin 26 of the West Rapti watershed

	Parameter	Description	Unit	Calibrated value	Minimum value	Maximum value
1	R_CN2.mgt	CN2 SCS runoff curve number for moisture		-0.07308	-0.1	0.1
2	V_CANMX.hru	Maximum canopy storage mm runoff	mm	0.094926	5	15
3	V_PLAPS.sub	Precipitation lapse rate	mm.km^{-1}	0.386864	-200	200
4	V_TLAPS.sub	Temperature lapse rate	°C.km^{-1}	35.07	-8	-4
5	V_ALPHA_BF.gw	Baseflow recession constant days groundwater	day $^{-1}$	-829.5	0	0.1
6	V_ALPHA_BF_D.gw	Alpha factor for groundwater recession curve of the deep aquifer	day $^{-1}$	397.125	0	1
7	A_GW_DELAY.gw	Groundwater delay time	day	0.02582	-30	90
8	A_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	mm	14.62025	-1000	1000
9	A_REVAPMN.gw	Threshold depth of water in the shallow aquifer for. "revap" or percolation to the deep aquifer to occur	mm	0.947389	-750	750
10	V_GW_REVAP.gw	Groundwater "revap" coefficient.		78.8625	0.02	0.1
11	R_SOL_AWC(..).sol	Available water capacity of the soil layer	mm/mm soil	13.71375	-0.05	0.05
12	V_ESCO.hru	Soil evaporation compensation factor		110.4825	0.85	0.95
13	V_SFTMP.bsn	Snowfall temperature	°C	-7.96318	-2	3
14	V_SMTMP.bsn	Snowmelt base temperature	°C	0.033899	-1	2
15	V_SMFMX.bsn	Maximum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	0.443958	2.5	4.5
16	V_SMFMN.bsn	Minimum melt rate for snow during the year	mm °C^{-1} day $^{-1}$	2.24	0	2.5
17	V_TIMP.bsn	Snowpack temperature lag factor		0.159122	0	1
18	V_SLSOIL.hru	Slope length for lateral subsurface flow	m	3.444425	0	150
19	V_LAT_TTIME.hru	Lateral flow travel time	days	0.656332	0	15

ANNEX C: CROP SCHEDULES FOR MAJOR CROPS ESTABLISHED IN THE TARAI AND MID-HILL REGION OF THE STUDY AREA

Table C1. Crop schedules for major crops established in the Tarai and Mid-Hills region of study area.

Rice	
Date	Practice
6/10	Tillage
6/11	Water impoundment
6/12	Planting
6/13	Fertilizer application
7/8	Release impoundment
7/15	Water impoundment
7/16	Fertilizer application
7/15	Irrigation
8/12	Release Impoundment
8/16	Water Impoundment
8/16	Irrigation
8/15	Fertilizer application
9/2	Fertilizer application
9/15	Release impoundment
11/8	Harvest

Spring rice	
Date	Practice
2/9	Tillage
2/11	Water impoundment
2/11	Irrigation
2/11	Planting
2/12	Fertilizer application
3/4	Release impoundment
3/11	water Impoundment
3/11	Irrigation
3/12	Fertilizer application
4/4	Release impoundment
4/12	Fertilizer application
5/4	Water impoundment
5/11	Irrigation
6/4	Release impoundment
6/9	Harvest

Wheat	
Date	Practice
11/15	Tillage
11/16	Planting
11/16	Fertilizer application
12/2	Irrigation
12/2	Fertilizer application
1/15	Fertilizer application
4/5	Harvest

Monsoon maize	
Date	Practice
5/10	Tillage
6/10	Planting
6/10	Fertilizer application
9/14	Fertilizer application
11/10	Harvest

Winter maize	
Date	Practice
11/14	Tillage
11/15	Planting
11/15	Irrigation
11/15	Fertilizer
12/25	Fertilizer
5/5	Harvest

Tomato	
Date	Practice
1/11	Tillage
5/11	Irrigation
11/11	Fertilizer application
5/12	Irrigation
11/12	Fertilizer application
5/1	Irrigation
11/1	Fertilizer application
7/2	Harvest

Potato	
Date	Practice
10/11	Tillage
15/11	Irrigation
15/11	Planting
5/12	Irrigation
11/12	Fertilizer application
5/1	Irrigation
5/2	Irrigation
11/2	Fertilize application
2/4	Harvest

Mungbean	
Date	Practice
4/4	Tillage
4/5	Irrigation
4/6	Planting
4/6	Fertilizer
4/26	Irrigation
5/14	Irrigation
6/10	Harvest

Lentil	
Date	Practice
10/15	Tillage
10/17	Planting
3/30	Harvest

Monsoon maize	
Date	Practice
5/10	Tillage
6/10	Planting
6/10	Fertilizer application
9/14	Fertilizer application
11/10	Harvest

Annex II – Report release workshop: a Framework for Sustainable and Inclusive Irrigation Development in Western Nepal

Above: Mr. Sagar Kumar Rai, Secretary, Ministry of Energy, Water Resources and Irrigation, delivers his opening remarks at the workshop. Source: CIMMYT.

Topic	Presenter	Date
Welcome and opening remarks	Mr. Sagar Kumar Rai, Secretary, MoEWRI	28 April, 2022
Presentation and discussion		**Key terms**
Mr. Rai highlighted several issues key to Nepal's irrigation development: • Only 40% of agricultural land in Nepal has year-round irrigation facilities – more emphasis is required on agriculture and water management. Due to the effects of climate change on irrigation, Nepal needs to focus on the climate resilience of irrigation, and link water and energy policies. • Promoting farmer-centric and GESI-responsive tools is required. This can be guided by the identification of land available for farming, but there is a lack of irrigation facilities. • Major efforts need to focus on improving lift irrigation through better electricity supplies in both the Tarai and the hills, and sustainable irrigation in the dry season. • Big and small scattered schemes can be managed in clusters of 40,000 or 50,000 ha. This allows for more context-specific management and solutions, especially for conjunctive use. • Diversion technology is being used to supply water-deficient areas with water from water-rich areas through basin integration in large projects, such as the Sunkoshi diversion project and the Kaligandaki–Tinau pipeline. • Working both at institution- and policy-level is ongoing including through the draft Irrigation Master Plan, being prepared to replace the 1994 Irrigation Master Plan. The new master plan will be published with assistance from ADB. • MoEWRI is actively supporting farmers with 80% to 100% subsidies on electricity and various irrigation technologies, including solar pumps. • The findings and recommendations of the framework for Sustainable and Inclusive Irrigation Development in Western Nepal are invaluable, and MoEWRI seeks to implement them together with its partners.		Surface water Groundwater Irrigation system Integrated river basin project **Questions raised**
Summary		
Mr. Sagar Kumar Rai introduced himself as a representative of the Ministry of Energy, Water Resources and Irrigation. He stressed the significance of long-term irrigation development, particularly during the dry season. He also stated that agriculture is a critical component for women's emancipation, and that as only a few women are involved in agriculture, irrigation would represent a very positive addition to women's empowerment. He also discussed the year-round irrigation projects and integrated river basin projects (the latter being large multi-purpose diversion projects such as at Kaligandaki–Tinau, Bhotekoshi, Kamala and Tamor). Referring to both sparsely located deep water resources and clustered shallow water resources, he commented on the development of water obtained from surface technology, and that no effective policies or implementation for government jurisdiction had been created. The draft Irrigation Master Plan 2019 had been drafted by three levels of government and many new projects have been introduced as a result of federalization. Farmers will receive a 80%–100% subsidy, according to the ministry. He concluded by giving his assurance that the resource project will be implemented.		

Topic	Presenter	Date
Remarks from USAID	Jason Seuc, Director, Economic Growth Office, USAID Nepal	28 April, 2022

Presentation and discussion

Mr. Seuc provided key insights into USAID's priorities and thinking on irrigation development in Nepal:

- To improve food security and resilience in Nepal, the agricultural sector faces a lot of challenges; however, Nepal's water resources offer large opportunities for intensifying agriculture through irrigation and thus also building resilience against drought and other shocks.
- Today only 35% of agricultural land has a year-round irrigation facility, while irrigation is a critical determinant of agricultural success, especially in the dry season.
- The consequences of COVID-19 for farmers are still high and strong efforts are needed to improve both the bio-physical aspects of production as well as strengthening the supporting infrastructure in an inclusive manner.
- The Framework for Sustainable and Inclusive Irrigation Development in Western Nepal can guide USAID's continued work, together with USAID partners and counterparts in Nepal, in ensuring that the country's agricultural sector contributes to a self-reliant and prosperous Nepal.

Key terms

Water resources

Irrigation

Agriculture system

Questions raised

Summary

Mr. Seuc spoke about the 75-year bilateral relationship between Nepal and USAID, water monitoring of surface and groundwater, and how irrigation is essential for agricultural development. He stated that irrigation is important for developing climate change resilience: irrigation is difficult during the dry season and climate change has exacerbated the situation. Cropping systems have also changed as a result of climate change. Finally, he stated that USAID and CIMMYT had the same paradigm for sustainable and inclusive irrigation.

Topic	Presenter	Date
Introduction to the Framework for Sustainable Irrigation Development in Western Nepal	Timothy J. Krupnik Innovation Science Lead for Asia, CIMMYT	28 April, 2022

Presentation and discussion

Dr. Krupnik provided insights and background information on the larger CSISA Activity, contextualizing the framework into broader agricultural development objectives:

- CSISA has worked for the benefit of farmers in Nepal for more than 10 years. USAID has provided additional support to alleviate economic stresses after COVID-19 and to provide insights on how to use irrigation for developing resilience in Nepal's agricultural system.
- The problem: 60% of agricultural land is unirrigated.
- The opportunity: this land can be irrigated.
- The Draft Irrigation Master Plan 2019 already does a good job at outlining how to adapt a to climate variability and use conjunctive use planning.
- But we need more focus on the decision-making problems that farmers face in using and accessing irrigation, and incorporate these into sustainable irrigation frameworks
- CSISA thus provides principles for developing irrigation through conjunctive use of surface water and groundwater, institution, GESI, and importantly both the private and public sector.
- To ensure sustainability, CSISA also piloted a digital monitoring system for groundwater, to help guide sustainable groundwater management.
- There are different options for irrigation which can significantly increase rice and wheat production and allow the production of diverse and nutritious crops.
- Operationally, it is critical that all levels of government are involved and also take a watershed level perspective to guide sustainable irrigation development. The framework provides scenarios which were co-designed with stakeholders across these levels.
- Lastly, changing the approach to water management is crucial but also requires more data and information systems, as we cannot manage what we cannot measure.

Key terms

Surface water

Groundwater

Conjunctive use

Irrigation

Questions raised

Summary

CSISA is working to support farmers, and USAID support increases their benefits. COVID-19 has been the leading economic stressor for farmers from 2020-2021. Irrigation can be buffered by developing agricultural resilience. The major problem is that 60% of land which can be irrigated remains unirrigated. The conjunctive use of surface and groundwater is the key to sustainable irrigation. Collected bio-physical data helps integrate fluctuations in groundwater level, groundwater monitoring and sustainable irrigation management.

Topic	Presenters	Date
Governance and socio-economic enablers	Manohara Khadka, Senior Researcher, IWMI Labisha Uprety, Senior Research Offier, IWMI	28 April, 2022

Presentation and discussion

Ms. Khadka and Ms. Uprety discussed the governance and socio-economic enablers that were researched to develop the framework:

- Inclusive irrigation requires addressing the systematic barriers and opportunities for irrigation use in Nepal including factors affecting irrigation access to purchasing technologies and unequal access to irrigation services.
- Addressing these factors requires taking into account the following six aspects:
  - Policy and governance
  - Public and private sectors
  - Investor resilience
  - Agriculture value chains
  - Irrigation supply chain
  - Gender Equality and Social Inclusion (GESI)
- Research into these aspects included data from six different sources:
  - Inventory and review of 51 sectoral policies
  - Review of 29 projects
  - Literature review
  - Telephone interviews
  - Thematic analysis
  - Cross-validation
- Policy and governance barriers and opportunities include:
  - Barrier: lack of policy and legal framework for water
  - Barrier: lack of multi-sectoral platform
  - Opportunity: empower women and marginalised groups
  - Opportunity: devolution of power in agricultural policies incl. the role of local government
  - Opportunity: cross-sectoral interventions
- Public and private sectors:
  - Barrier: little collaboration and partnerships on irrigation development.
  - Barrier: fertiliser issues including long tendering process and black market trade with India.
  - Opportunity: local government as a strong public-private partner.
  - Opportunity: climate resilient agriculture investments that GESI-response and include multi-stakeholder participation.
- Agriculture value chain:
  - Barrier: irrigation equipment not easily available for purchase as it is all imported and highly taxed.
  - Opportunity: build better irrigation supply chain including by improving tax rates for irrigation equipment.
  - Opportunity: solar irrigation is being extensively increased with a 60% subsidy for solar irrigation.
- Gender Equality and Social Inclusion:
  - Barrier: GESI provisions are not implemented in most policies and programs.
  - Barrier: women are underrepresented in the private sector thus also reducing access for women farmers to products and services.
  - Opportunity: business should be tapped for women to provide better jobs and better access to products and services.
  - GESI provisions outlined in the constitution need to be implemented throughout all levels of government, polices and programs.

Key terms

Systematic barriers and opportunities

GESI

Policy and governance

Agriculture value chains

Irrigation

Questions raised

Bharat Upadhyaya, Deputy Chief of Party, KISAN II Activity

1. What comes first: irrigation or agriculture?
2. How can irrigation technology be made women-friendly?

Summary

There are various dimensions to scaling sustainable and inclusive irrigation development. The research methodology involved an inventory, review, phone interviews, thematic analysis and validation. Each of these six dimension have several barriers and opportunities.

Topic	Presenter	Date
Reflection on the presentations	Deepak Ghimire, Secretary, MoEWRI	28 April, 2022

Presentation and discussion notes

Mr. Deepak Ghimire reflected upon the presentations, highlighting the importance of the framework for Lumbini province:

- The framework will be very useful to support policymaking at local and provincial levels in Nepal.
- During a recent field visit in Surkhet, 90% of participants in interaction with local residents were women (farmers) who reported irrigation is also a key problem for livestock and dairy farming, which provide very good income.
- Water sources are available 5 km upstream. NPR 2.5 million is required to bring water which can provide a 5400 ha command area; farmers mentioned that canals are constructed upstream; only 1500 ha of land in Lumbini province is irrigated.
- Irrigation faces several problems with machinery availability and maintenance, exacerbated by land fragmentation which increases travel costs for irrigation.
- Nepal's heavy imports of food grains can be curbed with better irrigation use.
- Hilly regions are often left barren as they are uneconomical to farm, with migration providing better income from abroad.
- It is important to think big and prioritize large irrigation systems and projects, and to expand net irrigation in winter for year-round irrigation.

Key terms

Irrigation system

Command area

Agriculture improvement

Migration

Economy

Questions raised

Summary

Mr. Ghimire offered an overview of the Activity, stating that 90% of farmers are women who make their living by selling cow and buffalo milk. During interviews with farmers, the majority underlined the importance of developing irrigation for agricultural improvement.

According to the study, the entire command area for irrigation is 5400 ha, but only 1500 ha has been fulfilled due to water seepage from the canal. Mr. Ghimire stated that Rupandehi district has a large amount of groundwater irrigation potential. Farmers are paying for irrigation themselves. The Government needs to prioritize irrigation. Agriculture's net return has declined, fallow land has expanded, and rising costs have forced farmers to relocate to urban areas. Large-scale projects such as the Kaligandaki Tinau diversion need to be implemented.

Topic	Presenter	Date
Bio-physical and technological enablers	Nirman Shrestha, IWMI (researcher, agricultural water management)	28 April, 2022

Presentation and discussions

Mr. Shrestha discussed the bio-physical and technological enablers of the research and the framework:

- In Nepal, 90% of water withdrawal is for irrigation, of which 80% is used from June to September; 39% of land is irrigated throughout the year and at least 40% of farmers use groundwater as primary source of irrigation; 30% of farmers intend to invest in groundwater.
- Irrigation development will require planned conjunctive use of surface water and groundwater, as the SWAT modeling results show that it is not possible to irrigate all areas from just one source.
- In the monsoon, surface water and groundwater are sufficient but there is a problem of timely availability. Almost all dry season irrigation uses groundwater.
- Assessment of groundwater basin interconnections and recharge is difficult, as too few data are available.
- Intensive groundwater irrigation scenarios may deplete groundwater resources in the long-term if not managed and monitored carefully.

Recommendations:

- Given the paucity of data and information on water resources, more data should be collected and made openly accessible.
- The policy–science interface needs strengthening.
- Source conservation upstream can contribute to sufficient availability downstream; in particular, canal schemes can recharge aquifers.
- There is a lack of training in field water management practices in both irrigation and agriculture programs and this should be enhanced through targeted digital advisories and climate services.
- Lack of GESI provision for women farmers contributes to lack of technologies reaching and being used by more farming households. Women also need better integration into the private sector and public decision-making.
- There is a need for more user-oriented management practice and institutional capacity to facilitate better work with farmers on operation and management.

Key terms

Water access

Agriculture water management

Groundwater and surface water

GESI provision

Farmers

Questions raised

1. There seem to be a need for action research to know more about crop diversification and to scale up the level of farmers. (Churna Bdr. Oli)
2. Much research shows groundwater is declining due to various anthropogenic activities but this research show the increment in groundwater level. How is this possible? (Mahendra K. Yadav, FAO, Nepal)
3. The research shows intensive use and abstraction increase groundwater level. How intense? (David Grist)

Summary

Both surface water and groundwater are utilized for irrigation according to their availability. Data on groundwater are not sufficient for research; any data should be open access. Field-based agricultural training is essential for building farmer capacity. GESI provision should be implemented. To ensure sustainability and inclusivity, farmers should be activated through institution capacity for operation and management.

Topic	Presenter	Date
Babai case study	Nirman Shrestha, IWMI (replacing Avay Risal)	28 April, 2022

Presentation and discussion

Mr. Shrestha presented the findings of the Babai watershed case study:

- Babai watershed covers Dang, Salyan and Bardiya districts with range of 52 m to 2800 m above sea level, and annual rainfall of 1400m. Monthly maximum daily temperature is 32°C; monthly minimum daily temperature is 7°C.
- Groundwater use has been increasing; the watershed has also experienced more floods and droughts.
- The case study used a bio-physical model (SWAT) to simulate water availability for different scenarios. The scenarios were built through participatory stakeholder workshops and investigated different climate change scenarios. Evaluation was largely focussed on availability of water resources, crop yields and sustainability.
- The results showed that it is possible to increase yields with intensified irrigation in a sustainable fashion if both surface and groundwater sources are used. In particular, short-duration varieties are likely to be most responsive, given the reduced impact of temperature stresses.
- Surface water upstream can increase recharge downstream by 10%, especially in canal irrigation areas; groundwater abstraction can reduce streamflow in the dry season.

Key terms

Babai watershed

Climate change analysis

Sustainability of water resources

Yield and production scenarios

Groundwater level

Questions raised

Conclusions and recommendations

- Just one source is not sustainable; intensive use can impact on the environment, requiring monitoring of groundwater levels.
- Conjunctive use of surface water and groundwater is required; this needs coordination between federal, provincial and local authorities within a basin.

Summary

The baseline model is prepared using two scenarios: climate change analysis and simulated irrigation development. The relationship between cropping patterns and change in groundwater level was observed. The conclusion was that there should be conjunctive use of surface water and groundwater, and that coordination between government authorities would be essential for sustainability.

Topic	Presenter	Date
Tying up the framework (wrapping up and ways forward)	Anton Urfels, Water & Food Security Specialist, CIMMYT Nepal	28 April, 2022

Presentation and discussion notes

Mr. Urfels offered concluding remarks and suggested ways forward:

- Enabling effective COVID-19 crisis response in Nepal through appropriate agricultural machinery, resilience-enhancing irrigation and entrepreneurship.
- Great history and successes of irrigation development and management in Nepal.
- New generation of ideas is required for addressing new challenges of today.
- Irrigation use is hindered by social, technical and bio-physical factors, as outlined in the framework.
- The framework seeks to complement existing policy documents (such as the Draft Irrigation Master Plan 2019) and to offer strategies and potential solutions for more successful implementation.
- Importantly, there is insufficient groundwater data available, and more work is required to understand recharge processes and ensure irrigation takes place within ecological boundaries.
- Irrigation and agricultural supply chains are also critical for offering meaningful and inclusive jobs which raise incomes through coordinated upgrading of the food system.
- Technologies and practices need to be adaptive to context, as different ones work for different farmers (e.g. women) and different environments (e.g. soil types).
- Irrigation development thus requires adaptive planning that helps farmers make better decisions and feedback learnings into ongoing programs.
- Better data systems can support both value chain upgrading and technology targeting while ensuring environmental sustainability.
- If done well and in a timely manner then irrigation development can strongly contribute to strengthening food security, environment, sustainability and gender issues for a prosperous and happy Nepal.

Key terms

Irrigation success

Use of technology

Adaptive planning

Agriculture value chains

Groundwater

Food security

Sustainability

Questions raised

Summary

Anton Urfels summed up the framework, underlining key points and making recommendations, and expressed his wishes for a prosperous and happy Nepal. He referred to irrigation successes in Nepal, the need for farmers to rely on rain for irrigation and for a framework for sustainable and inclusive irrigation. He advocated adaptive technology prioritization, a robust data and information infrastructure, and agricultural value chain expansion and upgrade.

Suggestions, questions and answers

Suggestion: Various research concludes that Nepal's groundwater system is very complex. The groundwater resource is highly essential, it is of utmost focus to deliver the output of research to as many people as possible.

Response: Research was conducted in Banke district on the possibility of digitizing groundwater monitoring; the result was positive. A workshop was therefore developed for piloting survey. Speaker acknowledged the technical support given by the team and recommended to keep supporting in future.

***Question* (Churna Bdr Oli):** Generally, groundwater research decrease is due to artificial reasons, but the research says it will increase. How is this possible?

***Answer* (Nirman Shrestha):** The model output is based on climate change research, which shows that precipitation will increase in future.

Questions by Bharat Upadhaya, Deputy Chief of Party, Kishan II Activity, Nepal:

1. The debate on whether to prioritize irrigation or agriculture always has been a topic of concern. Also, climate change has resulted in changes in cropping patterns and intensity. Relating to government, what might be a situational framework to direct both irrigation and agricultural development simultaneously?
2. The present Constitution has empowered agriculture jointly with other minor municipal projects – so the private sector can also assist the municipality to facilitate a sustainable and inclusive irrigation sector. What is your say on investment by the private sector into the irrigation sector, as farmers are ready to pay?

***Answer* to (2) by Labisha Upreti:** Considering Gujrat's water market integration scheme, it is great idea to introduce a water market for irrigation.

***Answer* to (1) by Nirman Shrestha:** Simultaneous development of agriculture and irrigation can be done by coordination of local government with the public.

Questions by Mahendra Kumar Yadav, FAO Nepal:

1. The research shows that intensive use induces increased draw-down – what is 'intensive use'?
2. To date it has not been discovered what will happen due to climate change, although research shows it will increase precipitation. How?

***Answer* by Nirman Shrestha:** Only one scenario was studied, showing that precipitation would increase. Not enough data is available – a different outcome is possible. So monitoring techniques need to be improved and increased.

Questions by David Grist, USAID

1. How does the water table work? How does the use of water upstream affect downstream?
2. Name some socio-economic women-friendly irrigation technology.

***Answer* to (1) by Nirman Shrestha, IWMI:** Not enough data is available; further study is needed. The outcome is based on findings rather than facts.

***Answer* to (2) by Labisha Upreti:** The solar pump demands less manual strength, which similarly is the case with the automated switch.

Topic	Presenter	Date
Thanks, concluding remarks	Dr. Govinda P. Sharma, Secretary, MoALD	28 April, 2022

Presentation and discussion notes

Dr. Govinda P. Sharma, Secretary, MoALD, expressed his great appreciation for the framework and the research reflected in it. He highlighted the following points:

- Sustainable irrigation is critical for boosting agricultural productivity and production in Nepal, both before and especially after COVID-19 and its effects.
- The most important question remains: What interventions can really help farmers on the ground?
- Supporting farmers needs a better understanding of how different technologies fit into the local context (such as soil types and socio-economic differences), which vary geo-spatially. This requires governance for digital agricultural services, able to support micro-zoning based upon remote sensing data and analysis.
- Supporting farmers also requires building climate resilience for different crops, better understanding and support of traditional systems, and practices of irrigation which may be scaled in future.
- The value chain roadmap is very important; the framework highlights the importance of further ground level research and information on how practically to upgrade value chains to support farmers and create jobs.
- As a next step, MoALD heartily welcomes further provincial research that can address these bottlenecks and demonstrate models.
- It is important to consider the nexus of water, energy and food to meet climate targets and ensure water-, energy- and food security, while building resilience to multi-hazard risks in agriculture.
- Importantly, the irrigation and agricultural sector need to work better together to support farmers in boosting their production, resilience, and income. The framework provides good guidelines for achieving this.

Key terms

Climate resilience irrigation system

Coping with geospatial diversity

Digital agriculture/ agricultural governance

Micro-zoning with remote sensing

Questions raised

Summary

Dr. Govinda P. Sharma's concluding remarks addressed the issue of a lack of a value chain roadmap for developing Nepal's food system, a question-mark over the system's performance and long-term viability, and the lack of soil-friendly technologies. Climate resilience irrigation, he argued, is difficult, but can be enhanced by targeting geographic diversity in bio-physical and social factors through digital agriculture and good digital governance which supports better remote sensing and micro-zonation. This can address the issue of farmers losing interest in agriculture because of difficulties and high risk. The framework provides very good examples of how better irrigation can be developed to improve Nepal's agriculture, and, he said, MoALD looks forward to working closely with irrigation programs to implement the recommendations.

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