International Water Management Institute

Innovation Brief

Framework for advancing water resource sustainability and climate resilience through local-scale hydrological modeling in the Ganges Delta

The Ganges Delta has large agricultural landscapes that provide food for millions of people. However, changes in climate and anthropogenic activities are causing water scarcity, floods and soil salinization, threatening food security and putting livelihoods at risk. To address these challenges, the CGIAR Initiative on Asian Mega-Deltas (AMD) is working to create more resilient, inclusive and productive deltas that can adapt to climate change and other stressors. The International Water Management Institute (IWMI) is undertaking local-scale hydrological modeling and developing Artificial Intelligence (AI)-powered salinity forecasting in the Ganges Delta Region to evaluate water and salinity dynamics.

This innovation brief outlines the methodological framework that will be used to develop a salinity forecasting system for the polders in Bangladesh using machine learning techniques, surface water and groundwater flow, and contaminant transport modeling to understand water and salinity dynamics and balances in the respective polders. The overall aim is to generate polder-specific knowledge that can optimize water management, increase agricultural productivity and ensure the long-term sustainability of this crucial deltaic system.

Woman farmer collecting fodder for her cows from the agricultural fields of the coastal Ganges Delta (*photo*: IRRI).

CGIAR | INITIATIVE ON Asian Mega-Deltas

Background

Asian mega-deltas are vast and ecologically vital regions that support millions of livelihoods and critical food baskets but face growing challenges such as water scarcity, flood risks and ecological degradation (Mondal and Wasimi 2007; Syvitski et al. 2009; Murshed et al. 2019; Nicholls et al. 2020). The sustainability of the Asian mega-deltas is critical for regional and global food security as it impacts livelihood and food security both within and beyond their borders. The landscapes in these deltaic systems are far more vulnerable to the ever-increasing surge in climate extremes, severe cyclones, sea level rise, increased freshwater salinization, soil salinization and land subsidence (Murshed and Kaluarachchi 2018; Nicholls et al. 2020). In addition, climate change accelerates the threats posed by these challenges and inflicts severe social and economic consequences. Without interventions, the impending climatic shifts are poised to exert further stress on the already fragile communities inhabiting the delta region. Further, it is anticipated to exacerbate issues such as food insecurity, poverty and hunger, and ultimately cause land degradation beyond repair (Mainuddin et al. 2021; Nicholls et al. 2016). Anticipated consequences include a troubling pattern of declining food security and a rise in poverty and malnutrition, which emphasizes the critical need for proactive interventions to protect the sustainability of these crucial regions (van Soesbergen et al. 2017; Islam and Al Mamun 2020).

The AMD initiative aims to create resilient, productive and inclusive deltas that can withstand climatic and other stressors while maintaining socio-ecological integrity. To achieve this, transformative technologies and practices need to be scaled efficiently at the local, regional and national levels. As part of the AMD initiative, IWMI is undertaking various activities to develop local-scale hydrological models in two deltas (the Ganges and the Mekong) to aid informed decision-making for enhancing water resilience in deltaic regions (Jampani and Matheswaran 2023).

The Ganges Delta

In Bangladesh, the polderization of floodplains in the Ganges-Brahmaputra Delta was undertaken to promote intensive agricultural production of fertile land and to reduce vulnerabilities to flood inundation, coastal erosion and salinity intrusion (Khan and Paul 2023; Shamsudduha et al. 2020, 2022). The polderized land areas were low-lying islands consisting mainly of alluvial sediment deposits. There are about 139 polderized land areas in Bangladesh spread across varying geographical extents in the Gangetic-Brahmaputra Delta Region. In over 2.8 million hectares (Mha) of the coastal zone, about 1.2 Mha are poldered. Over eight million people depend on the landscapes in these polders for their food security and livelihoods. The delicate balance between human activities and the hydrological processes of the floodplains is altered by the seawater intrusion coupled with increased human-induced disruptions in the polders, leading to significant emerging challenges (WLE 2015). The polders have modified the geomorphological development of the river channels and floodplains, resulting in waterlogging and drainage congestion within the polder systems. These are further complicated by rising sea levels and the influence of tidal surges.

Fisherman in a boat in the Ganges Delta (*photo*: WorldFish).

Rice planting in the wet season utilizing rainfall and river water via sluice gates in the coastal polders of the Ganges Delta (*photo*: IRRI).

The monsoon season facilitates crop production in the polders through ample water availability from rainfall and river systems. However, by the end of the season, some regions within the polder may remain waterlogged, impacting agricultural activities during the dry season. In this period, soil salinity hinders land productivity within the polders. Salinity poses a formidable challenge in both coastal and inland areas within these polders, frequently impacting crop yields, agricultural productivity and freshwater availability (Carcedo et al. 2022; Mondal et al. 2022). Tidal surges periodically introduce seawater into the agricultural land, contaminating soil and water sources and negatively impacting crop growth and agricultural productivity. Excessive irrigation and poor drainage infrastructures cause water to accumulate in the fields. As the water evaporates, salts from the underlying soil ascend to the surface, leading to soil salinity. Salt stress affects most of the crops, resulting in hindered growth and reduced crop quality. Further, saline water intrusion also impacts the drinking water systems, creating risk to human health (Khan et al. 2011; Khan and Paul 2023).

Reducing productivity gaps of the cropping system in the polder will hinge on efficient management of the water and salt concentrations. Even during the main *kharif* season (March to October), farmers lack forecast information on when to start agricultural activities due to the prevalent salinity conditions before the start of the monsoon season. In addition to the challenges posed by the interlinked riverine and coastal natural processes, maintaining desired water levels in the canal network for farmlands in various sections of the polders and satisfying aquacultural needs also increase the complexity.

The scarcity of real-time field data poses a significant challenge in making informed decisions, especially in the realm of hydrological and expert knowledge-based modeling. Accurate and timely information about precipitation, river flow, salinity, and other hydro-morphological and socio-economic parameters is crucial for understanding the dynamics of seawater and freshwater interactions. Hydrological modeling plays a pivotal role in addressing this challenge by providing a systematic framework to simulate and analyze the behavior of this interaction. These models leverage available data and scientific principles to predict water-related processes, facilitating a deeper understanding of complex regime change across the polders.

The application of Artificial Intelligence (AI) and machine learning (ML) techniques represents a groundbreaking approach to understanding and managing salinity dynamics. Traditional methods often struggle to capture the complexities of the interactions and identify zones influencing salinity. AI and ML models, however, excel in handling large datasets and identifying intricate patterns that may not be apparent through conventional analyses. By integrating such models with real-time field data, farmers can gain valuable insights into the current state of the polders, enabling them to take more effective and adaptive actions.

IWMI has engaged in several internal (AMD and other initiatives) and external discussions aiming to comprehend the ongoing activities in the Ganges Delta and explore how hydrological modeling can contribute to sustainable water and agricultural management. Based on insights gained through those deliberations, the following objectives were developed.

Objectives

- Create an AI/ML-driven salinity forecasting system for polder number 34/2p (near Khulna) in the Ganges Delta, enabling farmers to make informed decisions regarding the commencement of their agricultural seasons each year.

- Perform a thorough evaluation of the salt and water dynamics within the 34/2p polder system through integrating surface water and groundwater modeling coupled with hydrochemical modeling. This approach aims to gain insights into the factors that impact water and salinity dynamics within the specified polders.

Innovations

1. ***Salinity forecasting system using AI/ML in the Ganges Delta:*** This innovation entails the development of a salinity forecasting system for the 34/2p Khulna polder in the Ganges Delta, utilizing machine learning and deep learning techniques. The system will leverage readily available historical temporal datasets, including information on rainfall, groundwater level, groundwater quality, river salinity, river discharge, tidal height, land use/catchment characteristics and water extraction patterns within the polder. These data and other pertinent covariates will serve as proxies to predict salinity levels. This predictive model aims to provide valuable insights to farmers, informing them of the optimal timing to initiate their agricultural activities.

2. ***Comprehensive assessment of salt and water dynamics in polder systems:*** This innovation aims to conduct an in-depth analysis of salt and water dynamics within the 34/2p polder system. The approach combines an integrated modeling approach on surface water and groundwater interaction modeling with hydrochemical modeling, providing a detailed understanding of the factors influencing water and salinity dynamics and the mass balances in these polders. This comprehensive assessment will shed light on the area's unique environmental and hydrological conditions.

Methodological framework

Innovation 1

- IWMI endeavors include conducting a thorough and innovative analysis of salt and water dynamics within the 34/2p polder system, employing the pivotal role of AI/ML in advancing the understanding of salt and water dynamics, zonal thresholds mapping, and paving the way for sustainable water resource management in the 34/2p polder system (Figure 1).

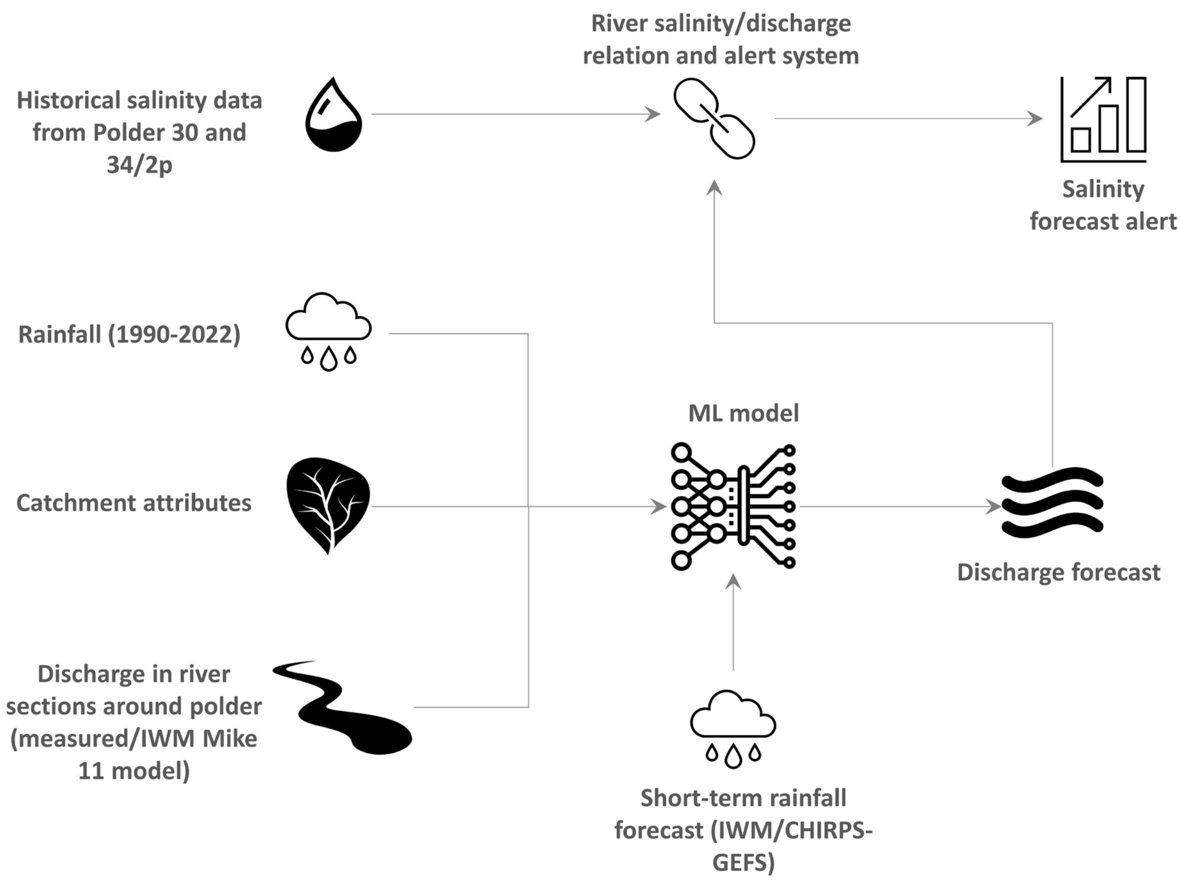

Figure 1. Framework for the data-driven model forecast of river salinity to advise on-field preparation.

Notes: ML - Machine learning; IWM - Institute of Water Modelling; CHIRPS - Climate Hazards Group InfraRed Precipitation with Station data; GEFS - Global Ensemble Forecast System

- AI/ML methodologies will leverage easily accessible historical temporal datasets on variables such as rainfall, groundwater level, groundwater quality, river salinity, tidal height, land use/catchment characteristics, water extraction patterns and other relevant variables within the polder to discern patterns and correlations.
- Zonal threshold mapping, facilitated by AI, will enable the identification of areas susceptible to salinity intrusion. Predictive analytics, driven by ML, will predict possible zonal segregation of fresh and saline water interface within the polder system with easily accessible input data/information to forecast salinity, aiding the water management strategies and suggesting adaptive measures.
- Programmable visualization tools (R/Python-based tools) will be employed to present complex results effectively.

Innovation 2

- Setting up surface water and groundwater interaction models at the polder scale to evaluate water flow regimes, irrigation return flows and saltwater intrusion dynamics (Figure 2).
- Modeling will possibly incorporate a comprehensive representation of both anthropogenic and geogenic activities along with the impacts of climate variability and change within the respective polder.
- Gathering primary and secondary data on irrigation conditions, groundwater levels, water quality, etc., in collaboration with local partners will serve as the basis for model calibration and validation, and conducting further scenario analyses.
- Understanding the migration of contaminants within the polders, encompassing salinity, agricultural runoff, and domestic and industrial pollutants, with the potential to impact human health and the agricultural ecosystem.
- Creating scenarios and implementing sustainable management strategies to evaluate the effect of different interventions aimed at enhancing agricultural productivity.

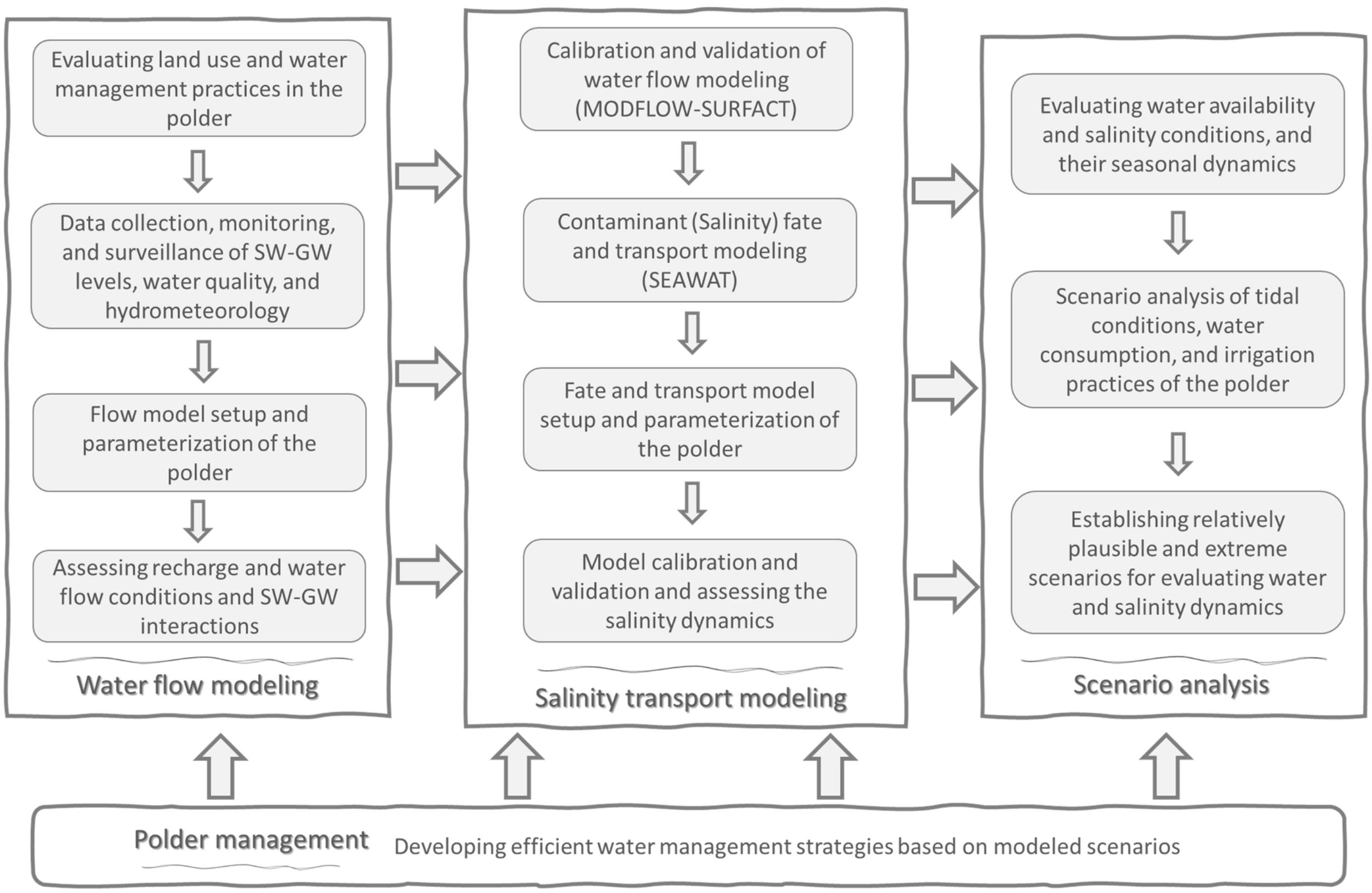

Figure 2. Framework to model water and salinity dynamics in the polder systems.

Notes: SW - surface water; GW - groundwater

Technical outputs by the end of 2024

- A research report/scientific article on the conceptual model of water and salinity dynamics in the Ganges Delta.
- A machine learning-based salinity forecasting system for the 34/2p polder in Khulna using various readily available covariates.
- A journal article on the review of the socio-hydrology of Asian mega-deltas.
- A peer-reviewed journal article or research report on water and salinity dynamics of the 34/2p polder to support integrated polder management plans.

Innovation beneficiaries

The innovations discussed here are beneficial to a number of stakeholders, including:

- **Government agencies:** Provide support to implement data-driven and evidence-based policies for water resource management and climate resilience of the polder systems in the Ganges Delta Region.
- **Local agriculture and water authorities:** Enhance decision-making capabilities by using robust modeling results of salinity and water use trends and the respective scenarios for overall water resources and irrigation water management, planning and allocation strategies of the respective polder. Additionally, the results provide sustainable management strategies based on integrated hydrological and salinity transport modeling for the polders in the Ganges Delta.
- **Researchers and academia:** Utilize the polder-specific water and salinity balances to develop more in-depth studies of the respective polder, further helping in the development of regional-scale models and contributing to scientific understanding and innovation in sustainable agriculture and the overall sustainability of the Ganges Delta.

Farmers at work in the aquaculture ponds of the Ganges Delta (*photo*: WorldFish).

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Fishing in the aquaculture ponds of the Ganges Delta (*photo*: WorldFish).

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CGIAR Initiative on Asian Mega-Deltas

The CGIAR Initiative on Asian Mega-Deltas aims to create resilient, inclusive, and productive deltas that maintain socio-ecological integrity, adapt to climatic and other stressors, and support human prosperity and wellbeing by removing systemic barriers to the scaling of transformative technologies and practices in the community, national and regional levels.
https://www.cgiar.org/initiative/asian-mega-deltas/

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