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INTEGRATED SIMULATION FRAMEWORK FOR THE IMPACTS OF LARGE DAMS—EXAMPLE OF THE GERD

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Efficient water resources management is essential for the sustainable development of nations, and large dams are an important tool for achieving this endeavor. Here, we present an integrated approach to simulating the impacts of large dams, integrating river systems infrastructure, hydrodynamic, and economywide models. We apply the framework to examine the biophysical, GDP, and distributional impacts of the Grand Ethiopian Renaissance Dam (GERD) on Sudan.

Background

Assessing the impacts of large dams requires a holistic approach

Ensuring sustainable access to water, energy, and food is a cornerstone for the economic development of societies. Dams have been employed for millennia to harness rivers for diverse purposes, such as flood control, drinking water supply, irrigation, industries, and hydropower generation. The past six decades have witnessed a surge in the construction of large dams, with approximately 58,000 such structures built, often in transboundary river basins that cover half of the Earth's land surface. Among these dams, close to half were designed for irrigation water supply, supporting 12-16 percent of global food production (Mulligan, Soesbergen, and Sáenz 2020). In 2020, hydro-electricity production, mostly associated with large dams, contributed 17 percent of the world's electricity generation. More than 3,700 large dams with at least 1 megawatt (MW) installed capacity are planned or under construction (Zarfl et al. 2015). While large dams offer social and economic benefits, they also affect access to river water and can contribute to transboundary and multisectoral conflicts.

With population and economic growth and increasing demand for water, energy, and food, competition among sectors and countries is intensifying in many river basins. To avert disputes over water resources and foster prosperity, the impacts of large dams must be assessed using a holistic approach that considers sectoral interlinkages. The costs and benefits of dams affect multiple economic sectors and vary spatially and temporally. Integrated engineering and economic planning of large dams could help maximize synergies and balance tradeoffs, thus enhancing efficiency and supporting prosperity.

The Nile River Basin

The Nile River, one of the longest rivers globally, is shared by 11 countries: Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, South Sudan, Tanzania, and Uganda. The Nile River Basin covers around 3

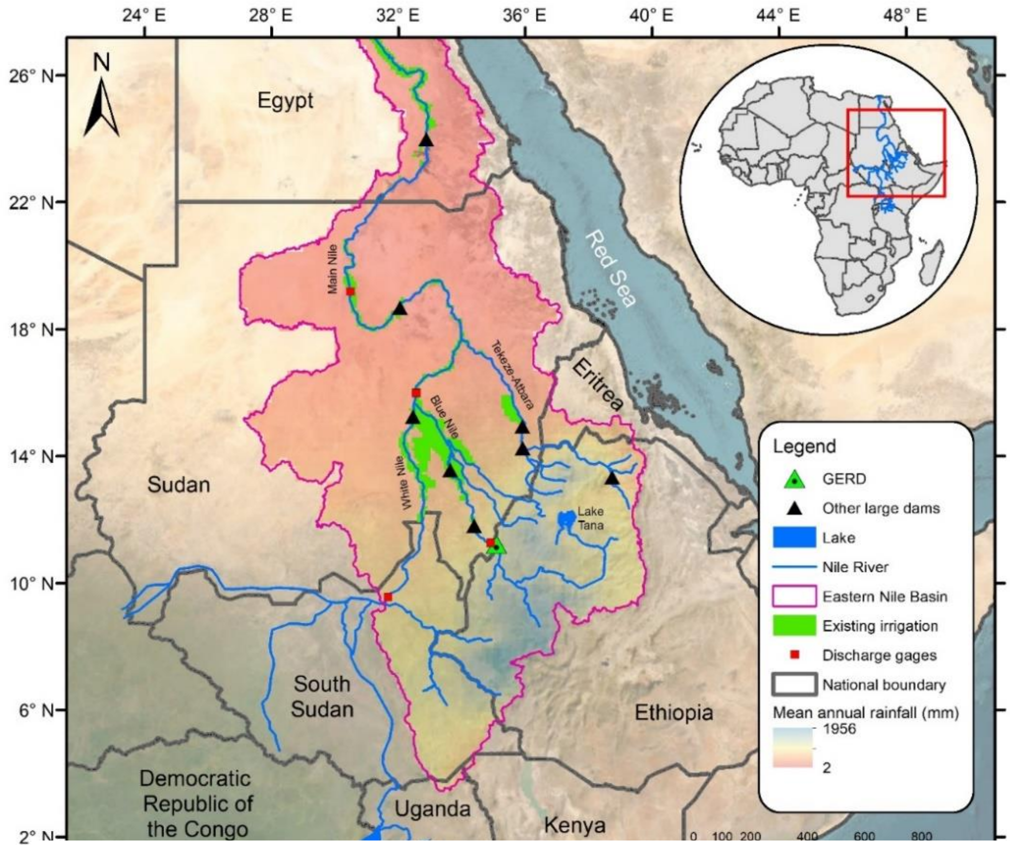

Figure 1 The Eastern Nile Basin and its mean annual rainfall, major dams, and existing irrigation

Note: GERD stands for Grand Ethiopian Renaissance Dam.

million km^2, constituting over 10 percent of Africa's area and 2 percent of the Earth's land surface. Figure 1 shows the Eastern Nile Basin, including the spatial distribution of rainfall, large dams, and major irrigation systems in Sudan. The Eastern Nile contributes over 85 percent of the Nile flow measured near the Sudan-Egypt border and is shared between Ethiopia, Eritrea, South Sudan, Sudan, and Egypt. The latter two countries account for most water use. The limited and stressed water resources and the geopolitically complex nature of the Eastern Nile have raised the potential for conflict between the riparian countries. Ethiopia is currently building the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile for hydropower generation. The initial filling of the dam's reservoir started in 2020 and is expected to be completed in 2024. The dam has a total storage capacity of 74 billion cubic meters (bcm), a planned generation capacity of 5150 MW, and a power factor of around 30 percent. The dam is expected to double overall electricity generation in Ethiopia, improve electricity access, and enhance economic growth. However, due to its anticipated downstream impacts, the dam has generated political tensions between Ethiopia, Sudan, and Egypt.

Integrated simulation framework for assessing the impacts of large dams

In this study, we developed a simulation framework to assess the impacts of large dams on multiple sectors. Figure 2 presents the framework, which includes three components: (1) a river system infrastructure model; (2) a two-dimensional hydrodynamic model; and (3) a Computable General Equilibrium (CGE) economywide model. We apply the framework to simulate the biophysical and economywide impacts of the GERD on Sudan, including hydropower generation, irrigation water supply, flood control, and Traditional Fired Clay Brick (TFCB) production. GERD is expected to increase hydropower production for Ethiopia, through the Eastern Africa Power Pool across East Africa, and through changes in river flows and power exports in Sudan. The dam is also expected to provide potential for irrigation expansion in Sudan and reduce flooding of built-up areas. Finally, GERD is expected to affect TFCB production in Sudan, which depends on the sediments the Nile

River transports during the flood season. Specifically, GERD is expected to reduce TFCB production by removing overland flows of sediments and by trapping a substantial share of the Blue Nile sediment load behind the dam.

River system infrastructure model

We developed a daily river system model for the Nile system in Sudan using the Python Water Resources (Pywr) tool (Tomlinson et al. 2020) using natural flow data for the period of 1985-2016. The three farthest upstream nodes considered in the model are the GERD and its inflow in Ethiopia, the flow at Malakal in South Sudan, and the Tekeze-5 Dam and its inflow in Ethiopia (Figure 3). The model includes eight reservoir nodes, 22 inflow nodes, 13 abstraction nodes for irrigation, one municipal abstraction node, five gaging stations, and channel losses for different river reaches. Additionally, dam operating rules, water demands, and water allocation priorities are used to drive model simulations to reflect historical system operations; the model performance was calibrated and validated based on observed dam releases and river flow at gaging stations at multiple locations.

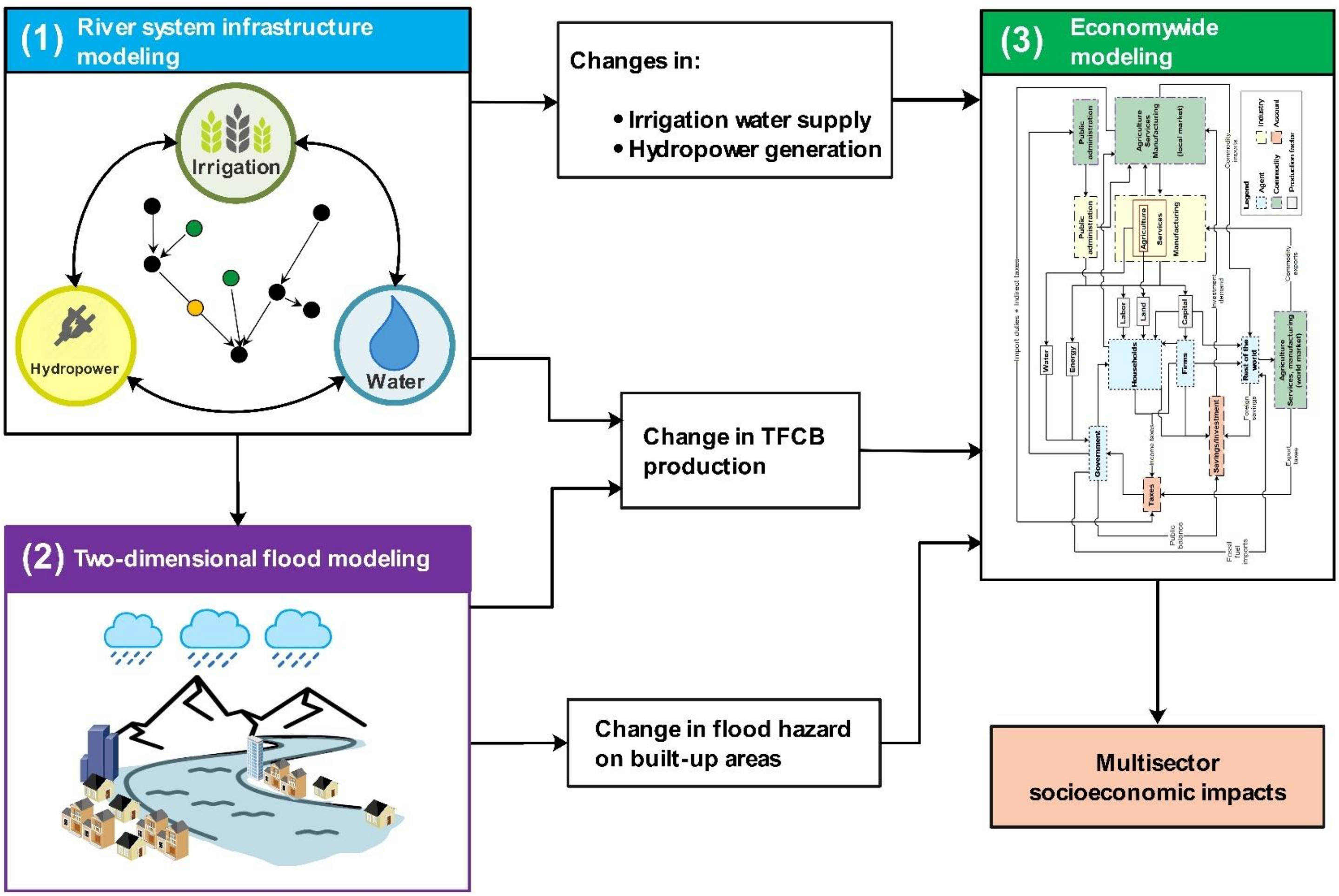

Figure 2 Integrated analytical framework for assessing the biophysical and socioeconomic impacts of operating large dams
Note: TFCB stands for Traditional Fired Clay Brick.

Two-dimensional hydrodynamic model

A hydrodynamic model was created and calibrated to simulate unsteady flow for the Blue and Main Nile River reaches in Sudan, aiming to quantify flood extent and depth. The simulation used the Hydrologic Engineering Center River Analysis System (HEC-RAS) software with a solution interval of one hour.

Economywide model

Economywide impacts of the GERD on different economic sectors in 2024 were modeled using the International Food Policy Research Institute's (IFPRI) standard CGE model, a recursive dynamic, single-country, and open economy model. The model considers the constraints that shape the economy, including budget constraints of economic actors, macro balances, and market constraints for factors and commodities. The model was calibrated to a 2019 Social Accounting Matrix (SAM) of Sudan (Randriamamonjy, Raouf, and Siddig 2023). We extended the SAM by incorporating detailed data on the TFCB, construction, hydropower, and irrigation sectors, as well as other data from the Central Bureau of Statistics of Sudan.

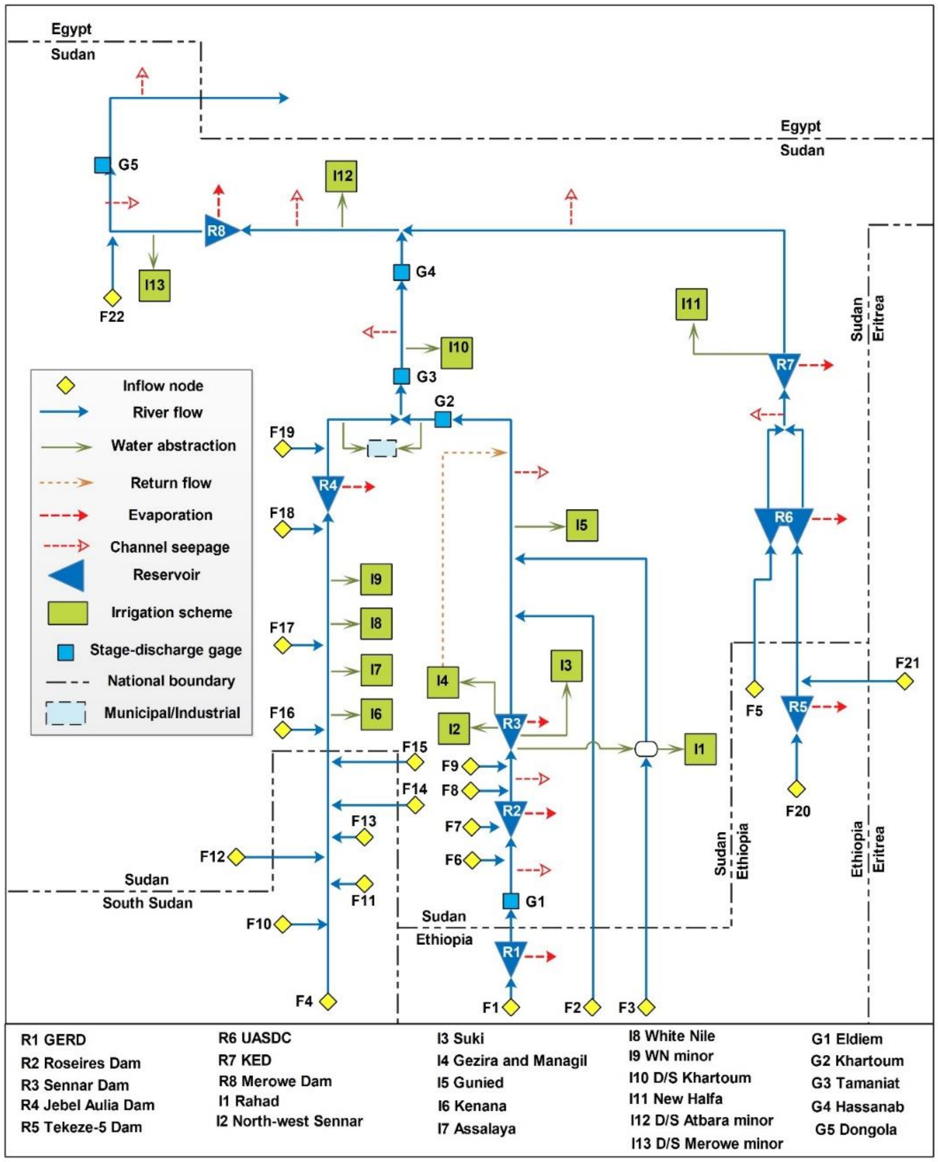

Figure 3 Schematic of the daily river system model from the GERD to the Sudan-Egypt border

Note: The sizes of different river system elements shown in the figure (for example, reservoirs and irrigation) do not reflect their actual sizes.

Model integration

The river system infrastructure component simulates hydropower generation, water supply to irrigation, and river flow patterns, while the hydrodynamic model estimates changes in flood extent and inundation of built-up areas linked to GERD. Calculated changes in river flow patterns and flood extent are used to infer the impact of the GERD on TFCB production.

Changes in hydropower production, irrigation water supply, TFCB production, and flood damages are transferred from the water to the economywide model, where they are applied, respectively, to hydropower capital, agricultural land, total factor productivity of the TFCB sector, and shocks to labor productivity and housing, reflecting changes in the destruction of property and health impacts.

Scenarios

Two simulation scenarios were formulated: (1) No GERD, and (2) With GERD. In the "No GERD" scenario, the Nile River system in Sudan follows historical operations. In the "With GERD" scenario, the dam is introduced into the system, and the operating rules of Roseires, Sennar, and Merowe dams in Sudan are adjusted to operate at high water levels to maximize hydro-electricity production with drawdown limited to meet water or energy deficits in drought years, as flood control in Sudan is already provided by GERD. The GERD was assumed to target power production of 1600 MW to maximize firm energy generation. To assess the sensitivity of GERD impacts to different hydrologic conditions, both scenarios were evaluated under high, median, and low river flow years. These flow years were selected based on simulated annual GERD outflows across 32 river flow sequences, each 32-years long, developed using the index-sequential method, that is, the lowest, highest, and median annual outflows across 1024 simulated years.

Example results

Biophysical impacts

With the GERD, hydro-electricity generation increases in Sudan from changes in river flows across all three river flow years. The largest boost in production occurs with the median flow year, an increase of 17.4 percent. This is followed by the high-flow year with an 11.6 percent increase and the low-flow year with a more modest increase of 3.6 percent. These findings suggest that introducing the GERD positively impacts hydropower generation in Sudan, particularly during median and high flow periods. On the other hand, the GERD does not substantially affect water supply to existing irrigation in Sudan. The changes in irrigation water supply remain marginal, with a negligible decrease of 0.4 percent in the median-flow year, a modest reduction of 1.4 percent in the low-flow year, and no change in the high-flow year. This result is consistent with previous studies examining the impacts of the GERD on water supply to existing irrigation in Sudan. The GERD operation would significantly affect TFCB production in Sudan, resulting in a decline of 92.0 percent of production across all scenarios, representing the contribution of the Blue Nile and the Main Nile to TFCB production in Sudan. This is because the seasonality in river flows is highly reduced, eliminating sediment replenishment on floodplains because the river does not overflow to the floodplains and most of the Blue Nile sediment load is trapped by the GERD.

Under the influence of the GERD, there is a discernible but modest decline in flooding of built-up areas in Sudan. This reduction varies from 0.9 percent in the high-flow year to 2.1 percent in the low-flow year. The impact on flood inundation is less pronounced in the high-flow year compared to the low-flow year because of the GERD's constraints on flood control during periods of extremely high flow.

Economywide impacts

Figure 4 presents the estimated percentage changes in Sudan's gross domestic product (GDP) and its key aggregate sectors—Agriculture, Industry, Manufacturing, and Services—simulated in 2024 due to the influence of the GERD across high, low, and median river flow scenarios. These changes are based on a discount rate of 0.5 percent. In the high-flow scenario, the agricultural sector GDP increases by 0.04 percent relative to the baseline; in the median-flow scenario, the increase is 0.08 percent and in the low-flow scenario, 0.01 percent. The industrial sector GDP is negatively impacted in two of the three river flow scenarios. In the high-flow scenario, industrial GDP declines by 0.2 percent and in the low-flow scenario by 0.26 percent; in the median-flow scenario, on the other hand, industrial GDP increases slightly by 0.06 percent. Manufacturing exhibits positive growth across all flow scenarios, as does the GDP of the services sector, albeit at lower levels. This translates to a negligible decline in Sudan's overall GDP under the high-flow scenario, while the low- and median-flow scenarios increase GDP by 0.026 percent and 0.11 percent, respectively. These variations highlight the complex interdependencies and tradeoffs associated with the GERD's influence on Sudan's economy.

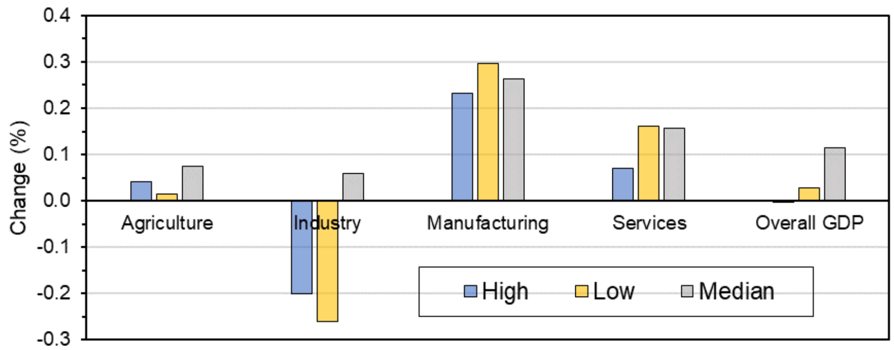

Figure 4 Percentage change in overall and aggregate sectoral GDP of Sudan in the “With GERD” scenario compared to the “No GERD” scenario under high, low, and median river flow years, simulated for 2024

Figure 5 illustrates the distributional aspects of the alternative scenarios as measured by Equivalent Variation across various household groups. The results suggest that all households will benefit from the GERD under the three flow scenarios, with the benefits varying across household groups. Results show that urban household groups in the second, third, and fourth income quintiles (hhd-u-02, hhd-u-03, and hhd-u-04) benefit most from the GERD as measured by their welfare gains. These gains are primarily driven by an increase in labor income, with a notable contribution from uneducated and primary school level male labor.

Conversely, the poorest urban quintile (hhd-u-01) and the poorest three rural quintiles (hhd-r-01, hhd-r-02, and hhd-r-03) experience the lowest welfare gains. This is chiefly because these households own lower shares of production factors used by benefiting sectors.

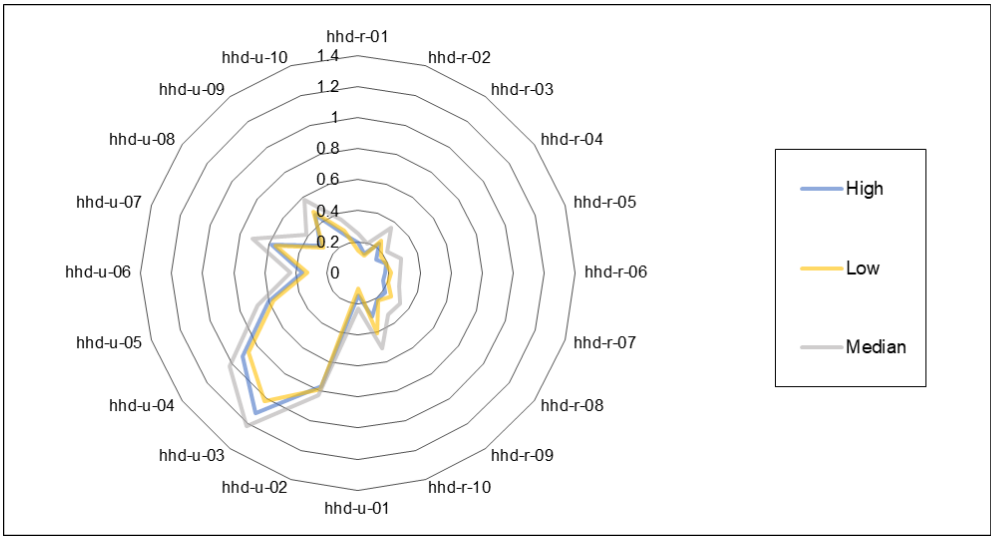

Figure 5 Percentage change in the Equivalent Variation of urban and rural household groups in the “With GERD” scenario compared to the “No GERD” scenario under low, high, and median river flow years

Notes: hhd stands for household, u stands for urban, and r stands for rural.

Conclusions

Large dams—given their multifaceted purposes encompassing flood control, drinking water supply, irrigation, industrial water supply, and hydropower generation—can significantly contribute to societal advancement. However, their benefits are often accompanied by adverse impacts, necessitating a comprehensive and integrated framework and approach to their evaluation. Here, we develop an analytical simulation framework to assess the multisector impacts of dams, emphasizing the interconnected nature of the various sectors influenced by these infrastructures. The framework integrates river system infrastructure, hydrodynamic, and economywide modeling to provide a holistic understanding of the implications of large dams. The results suggest that the benefits and burdens of such dams are seldom equitably shared and vary by river-flow levels. Decisionmakers should use the results of integrated modeling frameworks to assess sectoral and societal costs and benefits of new infrastructures, as well as identify social assistance measures to support those sectors and social groups that are adversely affected by dam infrastructures. This resonates with the broader discourse on sustainable development, emphasizing economic growth considering social and environmental implications.

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