Advancing water–energy–food–ecosystem nexus planning through digital tools: Applications from the Indus Basin

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Abstract: The interlinked challenges of water scarcity, rising energy demand, food security and the preservation of ecosystem services call for integrated planning approaches that explicitly account for trade-offs and synergies across sectors. Traditional sectoral approaches - where water, energy, agriculture, and the environment are managed independently - are no longer sufficient. They often overlook interdependence, leading to fragmented policies that resolve one problem while worsening others. To bridge this gap, three complementary platforms have recently been developed for the Indus Basin in Pakistan: *Water Productivity Atlas*, *Water Body Inventory* and a *Hydro-Economic Model*. Each tool addresses a unique dimension of the nexus to assess cross-sectoral trade-offs and support evidence-based decision-making.

The *Water Productivity Atlas* combines satellite-derived evapotranspiration, crop production statistics, and economic indicators to generate maps of physical (kg/m³), economic ($/m³), and nutritional (calorie/protein per m³) water productivity. This functionality helps identify geographic hotspots of inefficient water use and supports prioritization of interventions such as crop diversification, irrigation modernization and groundwater demand management across different districts. The *Water Body Inventory* developed using remote sensing, systematically maps and monitors the distribution of surface water bodies across Pakistan including rivers, lakes, small and large dams, and reservoirs. By capturing their spatial extent and seasonal to interannual variability, the tool provides reliable insights into blue water availability and its fluctuations under climate variability, infrastructure operations and changing irrigation demands. The *Hydro-Economic Model* integrates hydrological processes, agricultural production systems, and economic optimization into a single analytical framework. It allows policymakers to simulate alternative allocation scenarios, assess trade-offs between water for crops, energy generation and evaluate the impacts of policy choices under future climate change conditions. By linking resource allocation with economic outcomes, it directly supports evidence-based decisions for sustainable basin management.

When used together, these tools provide a foundation for Water–Energy–Food–Ecosystem (WEFE) nexus planning, enabling cross-sectoral assessments and evidence-based decision-making. They allow policymakers to visualize linkages across sectors, quantify trade-offs, and identify opportunities for synergies such as optimizing crop choices to reduce groundwater stress while safeguarding ecosystem services. This contribution introduces the functionality of the three tools, demonstrates their application in Pakistan and outlines their potential for scaling globally to strengthen WEFE nexus governance and climate resilience.

Keywords: *Water productivity, Hydro-economic modeling, Surface water monitoring, Digital tools, WEFE Nexus.*

