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COMMENTARY

Global humidity index integrating terrain and lateral water redistribution for enhanced hydrologic characterization

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Quantifying land water availability is fundamental to hydrology, ecology, and societal sustainability. The global aridity index, defined as the ratio of precipitation (P) to potential evapotranspiration (PET), has long served as a universal measure of climate-driven water balance.[1] Often termed the global humidity index (GHI=P/PET), this ratio fundamentally reflects the balance between atmospheric supply and demand. Its operational simplicity enables broad applications, ranging from climate change draught risk assessment to explaining plant functional traits and ecosystem distributions.

However, the climate-centric GHI omits a fundamental aspect of the hydrologic cycle: water movement is not limited to vertical land-atmosphere exchanges. Lateral transfers—including river discharge, flood dynamics, and groundwater flows—redistribute water by delivering resources from humid uplands to arid lowlands (Figure 1A).[2] This redistribution mitigates drought impacts and supports both ecosystems and societies in otherwise water-scarce regions. Crucially, it elucidates historical patterns of civilization in the Nile, Indus, and Mesopotamia river valleys, and explains the coexistence of savannas and forests under analogous climates yet distinct topographic positions.

Within this hydrological context, Míguez-Macho and Fan present a conceptual advance through the explicit integration of lateral water subsidies (Qlat) into the GHI framework.[3] Their topography-informed metric, GHI_topo = (P+Qlat)/PET, establishes a critical linkage between climatic drivers and landscape hydrology in water availability assessment (Figure 1).

This commentary examines these methodological developments, addresses the challenges in incorporating Qlat into the global-scale indices, and explores the prospects for developing a terrain-sensitive humidity framework.

METHODS FOR ASSESSING GLOBAL HUMIDITY INDEX

The conventional GHI relies solely on climate inputs, gained widespread adoption due to calculation simplicity and global data coverage. This formulation, however, implicitly assumes local hydrologic closure—ignoring regional-scale water transfers across the landscape. Consequently, it underestimates water availability in downgradient regions and fails to capture temporal lags in hydrologic response.

To quantify lateral redistribution, Míguez-Macho and Fan[3,4] employed the ASAP (as simple as possible) hydrology model at high spatial resolution (~1 km; Figures 1B-D), this yielded Qlat—the net inflow of surface and subsurface water. Integration of Qlat produces the topography-informed GHI_topo, enabling three critical advancements:

• Spatial redistribution capture: convergent lowlands exhibit higher effective humidity due to upstream subsidies.

• Temporal buffering representation: delayed groundwater contributions attenuate seasonal extremes and extend functional wet periods.

• Ecological realism: unlike conventional GHI, GHI_topo demonstrates stronger correlation with emergent vegetation greenness, underscoring its relevance to ecosystem functional interpretation.

The integration of lateral flow dynamics substantially advances hydrological assessment by (i) resolving ecosystem persistence contradictions, particularly sustaining riparian corridors and isolated oases in arid regions, (ii) capturing scale-dependent hydrologic–ecological linkages, and (iii) enabling more robust environmental decision-support for watershed management and climate adaptation planning. This implementation demonstrates novelty through its integration of global observations, scalable parameterization across diverse topographic settings, ecological validation with satellite-based proxies, and its potential to improve resilience modeling under changing hydroclimatic conditions.

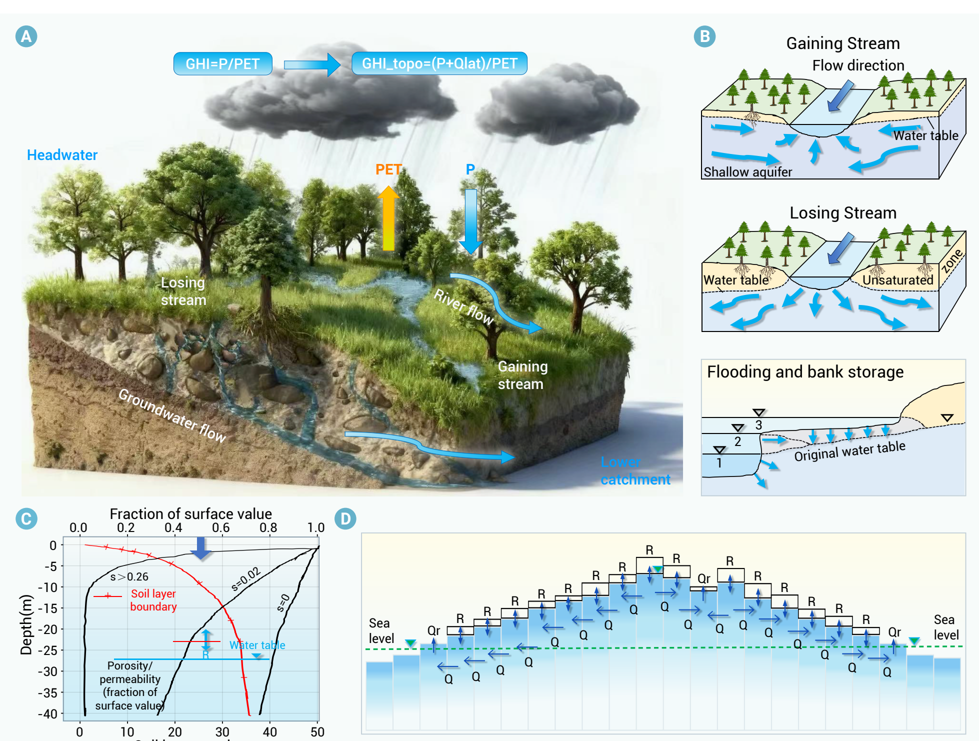

Figure 1. Conceptual framework for integrating lateral water subsidies (Qlat) into the global humidity index (GHI) (A) Representative lateral hydrologic pathways. (B-D) Schematic structure of the global model for estimating lateral water flows: (B) soil profile thickens with depth (top 40 m shown) while porosity and permeability decline with depth and slope. (C) two-way exchange between groundwater and rivers–floodplains within a grid cell, governed by water-level differences. (D) lateral groundwater convergence from uplands to lowlands, discharging as streams (Q) under sea-level boundary conditions.

CHALLENGES IN INTEGRATING LATERAL HYDROLOGIC FLOWS INTO THE GLOBAL HUMIDITY INDEX

Despite its theoretical merits, integrating Qlat into the GHI framework faces unresolved methodological and empirical constraints:

Model-Derived flux uncertainties. Qlat quantification remains contingent on global hydrologic models (e.g., ASAP), necessitating simplified parameterizations such as

Groundwater system knowledge gaps. Long groundwater transit timescales inherently conflict with synoptic GHI estimation. Aquifer characterization poses particular challenges due to sparse global data on hydrogeological properties (depth, connectivity, lithology) and near-absence of direct subsurface flux measurements. Current validation relies weakly on indirect proxies like vegetation indices and water-budget residuals, rendering Qlat estimates exceptionally vulnerable to equifinality,[5] particularly in remote or karst regions.

Unrepresented anthropogenic perturbations. Hydrologic regimes increasingly reflect engineered controls (e.g., irrigation, groundwater mining, reservoir operations, inter-basin water transfers) absent from naturalized Qlat frameworks. This omission risks systematic misestimation of actual water availability in human-modified basins (e.g., > 50% of global discharge systems). Endogenizing coupled human-water system feedbacks remains a fundamental barrier to reliable terrain-compensated water security assessments.

Dynamic hydroclimatic integration. Non-stationary climate forcing (shifting recharge zones, altered snow ephemerality, coastal saline intrusion) will redefine lateral transport magnitude-directionality. Coupling Qlat dynamics with Earth System Models (ESMs) further conflicts with closed-catchment paradigms dominating land-surface schemes. Mitigating computational-expense tradeoffs while retaining physical realism represents the pivotal challenge for climate-resilience applications of GHI_topo.

PROSPECTS FOR A TERRAIN-INFORMED GLOBAL HUMIDITY INDEX

While challenges persist, the integration of lateral flows into the global humidity index presents opportunities for advancing scientific understanding, policy formulation, and practice applications.

Ecological and biodiversity applications. The primary utility of GHI_topo lies in ecological research. By more accurately capturing vegetation dynamics, this index provides a realistic assessment of ecosystem water stress, thereby improving predictions of species distributions, vegetation shifts along topographic gradients, and ecosystem resilience to drought. In biodiversity conservation, GHI_topo facilitates the identification of critical refugia in arid regions—such as riparian forests, oases, and wetlands—where lateral water subsidies sustain these habitats. Incorporating Qlat into ecological models enhances the representation of terrain-mediated hydrological influences on species assemblages, enabling more effective strategies for habitat restoration and conservation planning.

Water resources management and policy implications. Beyond ecological applications, GHI_topo offers a refined framework for sustainable water resource management. Traditional indices often misrepresent water scarcity, overestimating deficits in lowland basins that receive upstream subsidies or underestimating stress in regions affected by significant flow diversions. By accounting for Qlat, planners can more reliably map water supply relative to demand across hydrological networks. This advancement strengthens the basis for transboundary water negotiations, irrigation allocations, and monitoring of dryland degradation. Notably, GHI_topo could serve as a key metric for agencies evaluating groundwater–surface water interactions under the United Nations Sustainable Development Goals (SDGs), particularly those pertaining to water security and ecosystem services.

Advances in modeling and data integration. Future research directions include refining the quantification of Qlat through improved datasets and modeling frameworks. Emerging satellite missions—such as GRACE (for groundwater storage) and SWOT (for surface water dynamics)—along with ground-based geophysical networks, enable multi-scale characterization of lateral water transfers. Integrating these observations with high-resolution topographic and lithological datasets will enhance the accuracy of global hydrologic models. Embedding Qlat into next-generation ESMs could elucidate feedback mechanisms between lateral water redistribution, land-atmosphere interactions, and carbon cycling, ultimately reducing uncertainties in climate-water-ecosystem projections.

Climate adaptation and resilience. GHI_topo also functions as a forward-looking tool for climate adaptation. As global warming exacerbates drought risks, the stabilizing influence of lateral water flows will become increasingly critical. Policymakers can leverage GHI_topo to identify regions with latent resilience sustained by terrain-driven water subsidies, as well as areas at heightened vulnerability due to declining recharge rates. These insights bear direct relevance to agricultural sustainability, urban water security, and disaster risk mitigation in drought-prone regions. Importantly, GHI_topo underscores that ecosystem resilience depends not only on climatic averages but also on hydrologic connectivity, advocating for adaptation strategies that preserve and restore natural water pathways.

CONCLUSION

The global humidity index has long been central to assessments of water stress, yet its climate-only formulation overlooks a defining feature of hydrologic systems: lateral flow. By incorporating Qlat, Míguez-Macho and Fan[3] demonstrate that water availability reflects both atmospheric inputs and landscape position. The introduction of GHI_topo moves the field toward a more hydrologically and ecologically realistic framework, with broad implications for understanding ecosystems, guiding water management, and projecting climate impacts. Future advances will depend on reducing uncertainties in groundwater flows, accounting for human interventions, and improving multi-scale representations.

REFERENCES

1. Greve P., Roderick M., Ukkola A., et al. (2019). The aridity index under global warming. *Environ. Res. Lett.* 14:124006. DOI:10.1088/1748-9326/ab5046
2. Jobbagy E. G., Nosetto M. D., Villagra P. E., et al. (2011). Water subsidies from mountains to deserts: Their role in sustaining groundwater - fed oases in a sandy landscape. *Ecol. Appl.* 21:678–694. DOI:10.1890/09-1427.1
3. Miguez-Macho G. and Fan Y. (2025). A global humidity index with lateral hydrologic flows. *Nature* 644:1-7. DOI:10.1038/s41586-025-09359-3
4. Miguez-Macho G. and Fan Y. (2021). Spatiotemporal origin of soil water taken up by vegetation. *Nature* 598:624–628. DOI:10.1038/s41586-021-03958-6
5. Fan Y., Li H. and Miguez-Macho G. (2013). Global patterns of groundwater table depth. *Science* 339:940–943. DOI:10.1126/science.1229881

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AUTHOR CONTRIBUTIONS

Yanqing Yang: Writing-review & editing,Writing–original draft, Software, Methodology, Investigation, Formal analysis, Data curation. Jiujiang Wu: Visualization, Software, Investigation, Data curation, Conceptualization. Xinyao Xie: Validation, Resources, Conceptualization. Wei Zhao: Visualization, Validation, Project administration, Funding acquisition, Data curation. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

Wei Zhao is an Editorial Board member of The Innovation Geoscience and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.