

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

| n/a                                 | Confirmed                                                                                                                                                                                                                                                                                      |
|-------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> The exact sample size ( <i>n</i> ) for each experimental group/condition, given as a discrete number and unit of measurement                                                                                                                               |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly                                                                                                                                               |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> The statistical test(s) used AND whether they are one- or two-sided<br><i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i>                                                                          |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> A description of all covariates tested                                                                                                                                                                                                                                |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons                                                                                                                                                   |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> For null hypothesis testing, the test statistic (e.g. <i>F</i> , <i>t</i> , <i>r</i> ) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted<br><i>Give P values as exact values whenever suitable.</i>                                |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings                                                                                                                                                                      |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes                                                                                                                                                |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Estimates of effect sizes (e.g. Cohen's <i>d</i> , Pearson's <i>r</i> ), indicating how they were calculated                                                                                                                                                          |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

|                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|-----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Data collection | <p>A repository containing and explaining all data and code used in this study is provided in a publicly accessible GitHub meta-repository here: <a href="https://github.com/JGCRI/niazi-etal_2024_nature-sustainability">https://github.com/JGCRI/niazi-etal_2024_nature-sustainability</a>. The repository could be used to reproduce the experiment as well as the analysis and the post-processing of the model outputs.</p> <p>Supporting data-repository that is to be used in combination with the main meta-repository is provided here: <a href="https://doi.org/10.5281/zenodo.6480465">https://doi.org/10.5281/zenodo.6480465</a></p> <p>Version of the Global Change Analysis Model (GCAM) used for this study is provided here: <a href="https://zenodo.org/record/6480465/files/gcam-5.7z?download=1">https://zenodo.org/record/6480465/files/gcam-5.7z?download=1</a> as a part of the data-repository.</p> <p>Data repository reference:<br/>Niazi, H., Wild, T., Turner, S., Graham, N., Hejazi, M., Msangi, S., Kim, S., Lamontagne, J., &amp; Zhao, M. (2022). Large Ensemble Dataset for Discovering Global Peak Water Limit of Future Groundwater Withdrawals Using 900 GCAM Runs (v0_initial_release) [Data set]. Zenodo. <a href="https://doi.org/10.5281/zenodo.6480465">https://doi.org/10.5281/zenodo.6480465</a></p> |
| Data analysis   | <p>R version 4.1.2 and packages as listed on top of *.R scripts in the following meta-repository were used for the analysis: <a href="https://github.com/JGCRI/niazi-etal_2024_nature-sustainability/tree/main/processing">https://github.com/JGCRI/niazi-etal_2024_nature-sustainability/tree/main/processing</a>. This link also provides a descriptive overview of all scripts and analysis methods used for this study.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

## Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

All data and code used in this study are provided in a publicly accessible meta-repository here: [https://github.com/JGCRI/niazi-etal\\_2024\\_nature-sustainability](https://github.com/JGCRI/niazi-etal_2024_nature-sustainability)

## Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research](#).

### Reporting on sex and gender

*Use the terms sex (biological attribute) and gender (shaped by social and cultural circumstances) carefully in order to avoid confusing both terms. Indicate if findings apply to only one sex or gender; describe whether sex and gender were considered in study design whether sex and/or gender was determined based on self-reporting or assigned and methods used. Provide in the source data disaggregated sex and gender data where this information has been collected, and consent has been obtained for sharing of individual-level data; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex- and gender-based analyses where performed, justify reasons for lack of sex- and gender-based analysis.*

### Population characteristics

*Describe the covariate-relevant population characteristics of the human research participants (e.g. age, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write "See above."*

### Recruitment

*Describe how participants were recruited. Outline any potential self-selection bias or other biases that may be present and how these are likely to impact results.*

### Ethics oversight

*Identify the organization(s) that approved the study protocol.*

Note that full information on the approval of the study protocol must also be provided in the manuscript.

## Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

## Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

### Study description

We conduct a large-ensemble modeling experiment using Global Change Assessment Model (GCAM) to simulate groundwater withdrawals across 235 water basins under 900 scenarios covering a variety of global change drivers over the 21st century.

### Research sample

The research sample contains 900 GCAM runs simulating groundwater withdrawals under multiple human-Earth system drivers of global change. The scenario ensemble members include five Shared Socioeconomic Pathways (SSPs), four Representative Concentration Pathways (RCPs), five global climate model outputs, three groundwater depletion limits, two surface water storage expansion regimes, and two historical groundwater depletion trends.

### Sampling strategy

Pair-wise combinatorial sampling of ensemble members was used to create 900 scenarios. Each ensemble member was paired with all other ensemble members in a simulation such that the ensemble member is the only variation in a simulation.

### Data collection

Data for the analysis and post-processing was queried from 900 GCAM output databases. Queries and queried outputs could be found here [https://github.com/JGCRI/niazi-etal\\_2024\\_nature-sustainability/tree/main/model/queries](https://github.com/JGCRI/niazi-etal_2024_nature-sustainability/tree/main/model/queries) and here [https://github.com/JGCRI/niazi-etal\\_2024\\_nature-sustainability/tree/main/model/outputs](https://github.com/JGCRI/niazi-etal_2024_nature-sustainability/tree/main/model/outputs) respectively.

### Timing and spatial scale

GCAM operates on a 5 year time-step temporally and on a spatially aggregated basin scale amounting to 235 basins globally.

### Data exclusions

Five of the SSP-RCP combinations (such as SSP3-RCP6.0 and RCP8.5 with SSP1-4) were deemed to be unfeasible and were excluded from the scenario sampling. The projections of future socioeconomic development doesn't allow the climate projections of radiative forcing at the end of the century stay in a feasible range.

## Reproducibility

The publicly accessible meta-repository contains all data and scripts required for reproducing the experiment ranging from steps related to setting up the model to running batch simulations to querying relevant outputs from 900 GCAM runs. Meta-repository could be accessed here: [https://github.com/JGCRI/niazi-et-al\\_2024\\_nature-sustainability](https://github.com/JGCRI/niazi-et-al_2024_nature-sustainability)

## Randomization

Describe how samples/organisms/participants were allocated into groups. If allocation was not random, describe how covariates were controlled. If this is not relevant to your study, explain why.

## Blinding

Describe the extent of blinding used during data acquisition and analysis. If blinding was not possible, describe why OR explain why blinding was not relevant to your study.

Did the study involve field work? ☐ Yes ☒ No

## Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

### Materials & experimental systems

| n/a                      | Involved in the study                                  |
|--------------------------|--------------------------------------------------------|
| <input type="checkbox"/> | <input type="checkbox"/> Antibodies                    |
| <input type="checkbox"/> | <input type="checkbox"/> Eukaryotic cell lines         |
| <input type="checkbox"/> | <input type="checkbox"/> Palaeontology and archaeology |
| <input type="checkbox"/> | <input type="checkbox"/> Animals and other organisms   |
| <input type="checkbox"/> | <input type="checkbox"/> Clinical data                 |
| <input type="checkbox"/> | <input type="checkbox"/> Dual use research of concern  |

### Methods

| n/a                      | Involved in the study                           |
|--------------------------|-------------------------------------------------|
| <input type="checkbox"/> | <input type="checkbox"/> ChIP-seq               |
| <input type="checkbox"/> | <input type="checkbox"/> Flow cytometry         |
| <input type="checkbox"/> | <input type="checkbox"/> MRI-based neuroimaging |

## Antibodies

## Antibodies used

Describe all antibodies used in the study; as applicable, provide supplier name, catalog number, clone name, and lot number.

## Validation

Describe the validation of each primary antibody for the species and application, noting any validation statements on the manufacturer's website, relevant citations, antibody profiles in online databases, or data provided in the manuscript.

## Eukaryotic cell lines

Policy information about [cell lines and Sex and Gender in Research](#)

## Cell line source(s)

State the source of each cell line used and the sex of all primary cell lines and cells derived from human participants or vertebrate models.

## Authentication

Describe the authentication procedures for each cell line used OR declare that none of the cell lines used were authenticated.

## Mycoplasma contamination

Confirm that all cell lines tested negative for mycoplasma contamination OR describe the results of the testing for mycoplasma contamination OR declare that the cell lines were not tested for mycoplasma contamination.

Commonly misidentified lines  
(See [ICLAC](#) register)

Name any commonly misidentified cell lines used in the study and provide a rationale for their use.

## Palaeontology and Archaeology

## Specimen provenance

Provide provenance information for specimens and describe permits that were obtained for the work (including the name of the issuing authority, the date of issue, and any identifying information). Permits should encompass collection and, where applicable, export.

## Specimen deposition

Indicate where the specimens have been deposited to permit free access by other researchers.

## Dating methods

If new dates are provided, describe how they were obtained (e.g. collection, storage, sample pretreatment and measurement), where they were obtained (i.e. lab name), the calibration program and the protocol for quality assurance OR state that no new dates are provided.

☐ Tick this box to confirm that the raw and calibrated dates are available in the paper or in Supplementary Information.

## Ethics oversight

Identify the organization(s) that approved or provided guidance on the study protocol, OR state that no ethical approval or guidance was required and explain why not.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

## Animals and other research organisms

Policy information about [studies involving animals](#); [ARRIVE guidelines](#) recommended for reporting animal research, and [Sex and Gender in Research](#)

## Laboratory animals

For laboratory animals, report species, strain and age OR state that the study did not involve laboratory animals.

## Wild animals

Provide details on animals observed in or captured in the field; report species and age where possible. Describe how animals were caught and transported and what happened to captive animals after the study (if killed, explain why and describe method; if released, say where and when) OR state that the study did not involve wild animals.

## Reporting on sex

Indicate if findings apply to only one sex; describe whether sex was considered in study design, methods used for assigning sex. Provide data disaggregated for sex where this information has been collected in the source data as appropriate; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex-based analyses where performed, justify reasons for lack of sex-based analysis.

## Field-collected samples

For laboratory work with field-collected samples, describe all relevant parameters such as housing, maintenance, temperature, photoperiod and end-of-experiment protocol OR state that the study did not involve samples collected from the field.

## Ethics oversight

Identify the organization(s) that approved or provided guidance on the study protocol, OR state that no ethical approval or guidance was required and explain why not.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

## Clinical data

Policy information about [clinical studies](#)

All manuscripts should comply with the ICMJE [guidelines for publication of clinical research](#) and a completed [CONSORT checklist](#) must be included with all submissions.

## Clinical trial registration

Provide the trial registration number from ClinicalTrials.gov or an equivalent agency.

## Study protocol

Note where the full trial protocol can be accessed OR if not available, explain why.

## Data collection

Describe the settings and locales of data collection, noting the time periods of recruitment and data collection.

## Outcomes

Describe how you pre-defined primary and secondary outcome measures and how you assessed these measures.

## Dual use research of concern

Policy information about [dual use research of concern](#)

### Hazards

Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

| No                       | Yes                      |                            |
|--------------------------|--------------------------|----------------------------|
| <input type="checkbox"/> | <input type="checkbox"/> | Public health              |
| <input type="checkbox"/> | <input type="checkbox"/> | National security          |
| <input type="checkbox"/> | <input type="checkbox"/> | Crops and/or livestock     |
| <input type="checkbox"/> | <input type="checkbox"/> | Ecosystems                 |
| <input type="checkbox"/> | <input type="checkbox"/> | Any other significant area |

## Experiments of concern

Does the work involve any of these experiments of concern:

| No                       | Yes                                                                                                  |
|--------------------------|------------------------------------------------------------------------------------------------------|
| <input type="checkbox"/> | <input type="checkbox"/> Demonstrate how to render a vaccine ineffective                             |
| <input type="checkbox"/> | <input type="checkbox"/> Confer resistance to therapeutically useful antibiotics or antiviral agents |
| <input type="checkbox"/> | <input type="checkbox"/> Enhance the virulence of a pathogen or render a nonpathogen virulent        |
| <input type="checkbox"/> | <input type="checkbox"/> Increase transmissibility of a pathogen                                     |
| <input type="checkbox"/> | <input type="checkbox"/> Alter the host range of a pathogen                                          |
| <input type="checkbox"/> | <input type="checkbox"/> Enable evasion of diagnostic/detection modalities                           |
| <input type="checkbox"/> | <input type="checkbox"/> Enable the weaponization of a biological agent or toxin                     |
| <input type="checkbox"/> | <input type="checkbox"/> Any other potentially harmful combination of experiments and agents         |

## ChIP-seq

### Data deposition

- ☐ Confirm that both raw and final processed data have been deposited in a public database such as [GEO](#).
- ☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links

May remain private before publication.

For "Initial submission" or "Revised version" documents, provide reviewer access links. For your "Final submission" document, provide a link to the deposited data.

Files in database submission

Provide a list of all files available in the database submission.

Genome browser session  
(e.g. [UCSC](#))

Provide a link to an anonymized genome browser session for "Initial submission" and "Revised version" documents only, to enable peer review. Write "no longer applicable" for "Final submission" documents.

### Methodology

Replicates

Describe the experimental replicates, specifying number, type and replicate agreement.

Sequencing depth

Describe the sequencing depth for each experiment, providing the total number of reads, uniquely mapped reads, length of reads and whether they were paired- or single-end.

Antibodies

Describe the antibodies used for the ChIP-seq experiments; as applicable, provide supplier name, catalog number, clone name, and lot number.

Peak calling parameters

Specify the command line program and parameters used for read mapping and peak calling, including the ChIP, control and index files used.

Data quality

Describe the methods used to ensure data quality in full detail, including how many peaks are at FDR 5% and above 5-fold enrichment.

Software

Describe the software used to collect and analyze the ChIP-seq data. For custom code that has been deposited into a community repository, provide accession details.

## Flow Cytometry

### Plots

Confirm that:

- ☐ The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).
- ☐ The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).
- ☐ All plots are contour plots with outliers or pseudocolor plots.
- ☐ A numerical value for number of cells or percentage (with statistics) is provided.

### Methodology

Sample preparation

Describe the sample preparation, detailing the biological source of the cells and any tissue processing steps used.

Instrument

Identify the instrument used for data collection, specifying make and model number.

|                           |                                                                                                                                                                                                                                                       |
|---------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Software                  | <i>Describe the software used to collect and analyze the flow cytometry data. For custom code that has been deposited into a community repository, provide accession details.</i>                                                                     |
| Cell population abundance | <i>Describe the abundance of the relevant cell populations within post-sort fractions, providing details on the purity of the samples and how it was determined.</i>                                                                                  |
| Gating strategy           | <i>Describe the gating strategy used for all relevant experiments, specifying the preliminary FSC/SSC gates of the starting cell population, indicating where boundaries between "positive" and "negative" staining cell populations are defined.</i> |

☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

## Magnetic resonance imaging

### Experimental design

|                                 |                                                                                                                                                                                                                                                                   |
|---------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Design type                     | <i>Indicate task or resting state; event-related or block design.</i>                                                                                                                                                                                             |
| Design specifications           | <i>Specify the number of blocks, trials or experimental units per session and/or subject, and specify the length of each trial or block (if trials are blocked) and interval between trials.</i>                                                                  |
| Behavioral performance measures | <i>State number and/or type of variables recorded (e.g. correct button press, response time) and what statistics were used to establish that the subjects were performing the task as expected (e.g. mean, range, and/or standard deviation across subjects).</i> |

### Acquisition

|                               |                                                                                                                                                                                           |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Imaging type(s)               | <i>Specify: functional, structural, diffusion, perfusion.</i>                                                                                                                             |
| Field strength                | <i>Specify in Tesla</i>                                                                                                                                                                   |
| Sequence & imaging parameters | <i>Specify the pulse sequence type (gradient echo, spin echo, etc.), imaging type (EPI, spiral, etc.), field of view, matrix size, slice thickness, orientation and TE/TR/flip angle.</i> |
| Area of acquisition           | <i>State whether a whole brain scan was used OR define the area of acquisition, describing how the region was determined.</i>                                                             |
| Diffusion MRI                 | <input type="checkbox"/> Used <input type="checkbox"/> Not used                                                                                                                           |

### Preprocessing

|                            |                                                                                                                                                                                                                                                |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Preprocessing software     | <i>Provide detail on software version and revision number and on specific parameters (model/functions, brain extraction, segmentation, smoothing kernel size, etc.).</i>                                                                       |
| Normalization              | <i>If data were normalized/standardized, describe the approach(es): specify linear or non-linear and define image types used for transformation OR indicate that data were not normalized and explain rationale for lack of normalization.</i> |
| Normalization template     | <i>Describe the template used for normalization/transformation, specifying subject space or group standardized space (e.g. original Talairach, MNI305, ICBM152) OR indicate that the data were not normalized.</i>                             |
| Noise and artifact removal | <i>Describe your procedure(s) for artifact and structured noise removal, specifying motion parameters, tissue signals and physiological signals (heart rate, respiration).</i>                                                                 |
| Volume censoring           | <i>Define your software and/or method and criteria for volume censoring, and state the extent of such censoring.</i>                                                                                                                           |

### Statistical modeling & inference

|                                                                           |                                                                                                                                                                                                                         |
|---------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Model type and settings                                                   | <i>Specify type (mass univariate, multivariate, RSA, predictive, etc.) and describe essential details of the model at the first and second levels (e.g. fixed, random or mixed effects; drift or auto-correlation).</i> |
| Effect(s) tested                                                          | <i>Define precise effect in terms of the task or stimulus conditions instead of psychological concepts and indicate whether ANOVA or factorial designs were used.</i>                                                   |
| Specify type of analysis:                                                 | <input type="checkbox"/> Whole brain <input type="checkbox"/> ROI-based <input type="checkbox"/> Both                                                                                                                   |
| Statistic type for inference<br>(See <a href="#">Eklund et al. 2016</a> ) | <i>Specify voxel-wise or cluster-wise and report all relevant parameters for cluster-wise methods.</i>                                                                                                                  |
| Correction                                                                | <i>Describe the type of correction and how it is obtained for multiple comparisons (e.g. FWE, FDR, permutation or Monte Carlo).</i>                                                                                     |

Models & analysis

|                                               |                                                                       |                                                                                                                                                                                                                           |
|-----------------------------------------------|-----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| n/a                                           | Involvement in the study                                              |                                                                                                                                                                                                                           |
| <input type="checkbox"/>                      | <input type="checkbox"/> Functional and/or effective connectivity     |                                                                                                                                                                                                                           |
| <input type="checkbox"/>                      | <input type="checkbox"/> Graph analysis                               |                                                                                                                                                                                                                           |
| <input type="checkbox"/>                      | <input type="checkbox"/> Multivariate modeling or predictive analysis |                                                                                                                                                                                                                           |
| Functional and/or effective connectivity      |                                                                       | Report the measures of dependence used and the model details (e.g. Pearson correlation, partial correlation, mutual information).                                                                                         |
| Graph analysis                                |                                                                       | Report the dependent variable and connectivity measure, specifying weighted graph or binarized graph, subject- or group-level, and the global and/or node summaries used (e.g. clustering coefficient, efficiency, etc.). |
| Multivariate modeling and predictive analysis |                                                                       | Specify independent variables, features extraction and dimension reduction, model, training and evaluation metrics.                                                                                                       |