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Groundwatersheds of protected areas reveal globally overlooked risks and opportunities

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Abstract

Protected areas are a key tool for conserving biodiversity, sustaining ecosystem services and improving human well-being. Global initiatives that aim to expand and connect protected areas generally focus on controlling ‘above ground’ impacts such as land use, overlooking the potential for human actions in adjacent areas to affect protected areas through groundwater flow. Here, we assess the potential footprint of these impacts by mapping groundwatersheds. We find that over five in six protected areas globally (85%) have groundwatersheds that are underprotected. Half of all protected areas have a groundwatershed with a spatial footprint that lies predominantly (i.e., at least 50%) outside of the protected area’s boundary. These findings highlight a widespread potential risk to protected areas from activities affecting groundwater within their groundwatersheds, underscoring the need for groundwatershed-based protection measures. Delineating groundwatersheds can catalyze needed discussions about protected

area connectivity and robustness, and investments in groundwatershed conservation and management can help protect groundwater-dependent ecosystems from external threats.

[start of main text]

Protected areas are fundamental tools for safeguarding biodiversity and play an important role in improving human well-being and sustaining ecosystem services[1–5]. Yet, current approaches to land protection have had clear limitations in regard to conserving freshwater ecosystems and species, which have shown staggering declines[6,7] One frequently discussed reason for the poor performance of protection initiatives is the lack of consideration applied to hydrologically connected freshwater systems outside (i.e., upstream) of protected areas[8,9], on which terrestrial and aquatic ecosystems found within their boundaries depend. With the development of the Convention on Biological Diversity's Post-2020 Global Biodiversity Framework, members of the conservation community have advocated for an expansion to the network of protected areas to cover 30% of terrestrial, inland water, and sea areas by 2030[10]. Yet, the need to manage human activities in connected lands and waters outside protected areas is absent from effectiveness discussions and indicators[11]. While connecting protected area initiatives to surface water processes is an important step, and hundreds of watersheds are already included in the World Database on Protected Areas, these efforts are undermined if equal consideration is not given to groundwater systems. Doñana National Park (Spain)[12,13] and Grand Canyon National Park (USA)[14] are two iconic examples of protected areas facing impacts from activities occurring outside of the protected area, such as agricultural drainage, mining, and groundwater pumping, that are transmitted to the protected area through groundwater.

The consideration and management of surrounding groundwater becomes increasingly important as land and water use intensifies around many protected areas[2,15]. Yet, no study has systematically investigated the potential for human activities outside of protected areas to impact terrestrial and aquatic groundwater-dependent ecosystems (GDEs) found within protected areas through groundwater flow (Fig. 1). Lateral groundwater flow supplies a significant proportion of water used by vegetation[16], and changes in land use or land cover can impact downgradient terrestrial ecosystems by changing the quantity and distribution of groundwater[17,18]. Groundwater pumping can reduce streamflow and drive streams from perennial to intermittent, ephemeral, or even disconnected[19,20]. Since groundwater provides distinct chemical and temperature attributes and can transmit contaminants such as nutrients[21], changes in groundwater levels and flow can introduce pollutants or otherwise alter water quality in protected areas[22].

In this study, we estimate the area from which human impacts may propagate to protected areas through groundwater flow systems. We employ a generic, reproducible workflow to map groundwatersheds for GDEs within protected areas (Box 1). We conclude by identifying risks posed to existing protected areas based on levels of human activity and land use modification within underprotected portions of groundwatersheds and discuss opportunities for improved conservation outcomes.

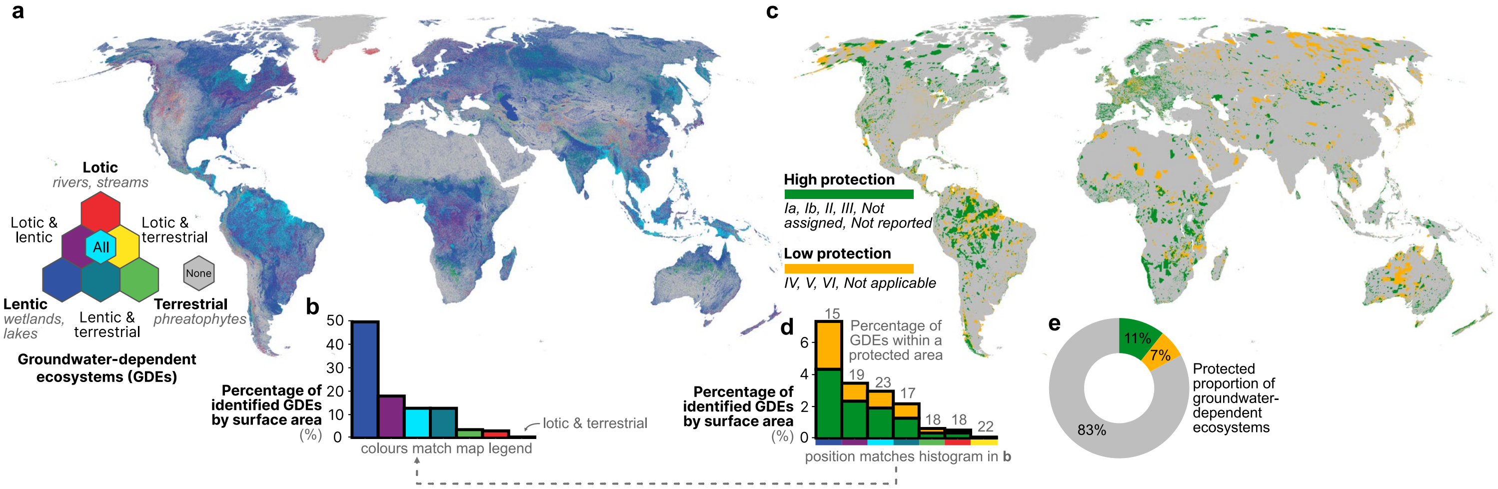


Fig. 1. Groundwater-dependent ecosystems (GDEs) and protected areas. **(a)** Location and co-occurrence of groundwater-dependent ecosystems per grid cell, based on data from refs.[23–27]. (**b**) Area distribution of GDE types. (**c**) Spatial distribution of protected areas[28]. We map groundwatersheds for the "high protection" class of protected areas and not for the "low protection" class. (**d**) Area distribution of GDEs within protected areas. (**e**) Proportion of all GDEs within protected areas.

Box 1: What are groundwatersheds?

*Note: Key terms are **bolded** and summarized at the bottom of the box.*

A **groundwatershed** is the contributing area from which a groundwater system flows to a feature or set of features of interest (Fig. 2). In this respect, groundwatersheds are the groundwater analog of surface watersheds. The groundwatershed concept was first introduced by Haitjema[29] to evaluate groundwater residence times, and similar concepts have been called *groundwater catchments*[30], *groundwater basins*[31], and mapping of *groundwater divides*[32]. However, the concept has seen limited uptake in water science and management, possibly owing to groundwater being an often overlooked resource and also possibly due to some characteristic differences between groundwatersheds and surface watersheds that make their delineation and use more challenging.

In arid environments, flat topographies, and regions with complex geologies, groundwatershed divides can be spatially unaligned with surface watershed divides[33]. Groundwatersheds also differ from surface watersheds in their ability to fluctuate with time. Whereas surface watersheds are defined by static topography, groundwatersheds are dynamic and their size and shape can change due to pumping, climate change, land use change, or seasonality. Therefore, groundwatersheds can be affected by a multitude of natural and human factors. However, in this analysis, we expect the majority of each groundwatershed's spatial extent to be consistent through time as fluctuations in the water table will only correspond to changes in the groundwatershed extent if the locations of water table divides are altered.

Here, we derive groundwatersheds using the water table surface instead of the land surface in a standard watershed delineation algorithm (see Methods). Using the water table surface to derive groundwatersheds enables a computationally simple approach to delineate groundwatershed extents. This approach generates groundwatersheds that reflect shallow, local groundwater flow systems, but does not represent nested, regional groundwater flow systems that require particle-tracking simulations that are currently infeasible at the global scale (Supplementary Fig. 1).

The groundwatersheds we derive in this study are of the world's **protected areas**. Unlike surface watersheds, we do not use river outlets as outlet locations in our groundwatershed delineation approach. Instead, we use the locations of **groundwater-dependent ecosystems** (Fig. 1a and described below) that lie within protected areas (Fig. 1b) as outlet locations. Thus, we do not derive contributing areas of groundwater flow for one location per protected area, but for all groundwater-dependent ecosystems within each protected area.

We identify groundwater-dependent terrestrial and aquatic ecosystems using datasets of groundwater-dependent wetlands, root zone intersections with the water table and perennial surface water features, since there is no existing global dataset of groundwater-dependent ecosystems[34]. The GDEs we identify in this study do not represent a comprehensive and refined global database but rather indicate locations where these ecosystems can potentially occur over the Earth.

To evaluate the potential importance of groundwatersheds and analyze their relationship with protected areas globally, we defined two metrics (Fig. 2c): relative groundwatershed size (RGS) and the underprotected groundwatershed ratio (UGR). RGS is an ecohydrological index representing size of the groundwatershed relative to the size of groundwater-dependent ecosystems within the groundwatershed. UGR is primarily a socio-hydrological conservation index that represents the underprotected proportion of each groundwatershed.

Groundwatersheds: Contributing areas of shallow, local groundwater flow to a feature.
Protected areas: IUCN protected area categories Ia, Ib, II, and III.
Underprotected areas: All areas outside of protected areas, as defined above. We use the term underprotected rather than unprotected as other forms of protection can exist in these areas, such as the European Union Water Framework Directive or California's Sustainable Groundwater Management Act.
Groundwater-dependent ecosystems (GDEs): Terrestrial or aquatic ecosystems that contain species or habitats that rely on groundwater[34]. Lotic GDEs have running water (e.g., rivers and streams), whereas lentic GDEs refer to those with standing waters (e.g., lakes and wetlands).

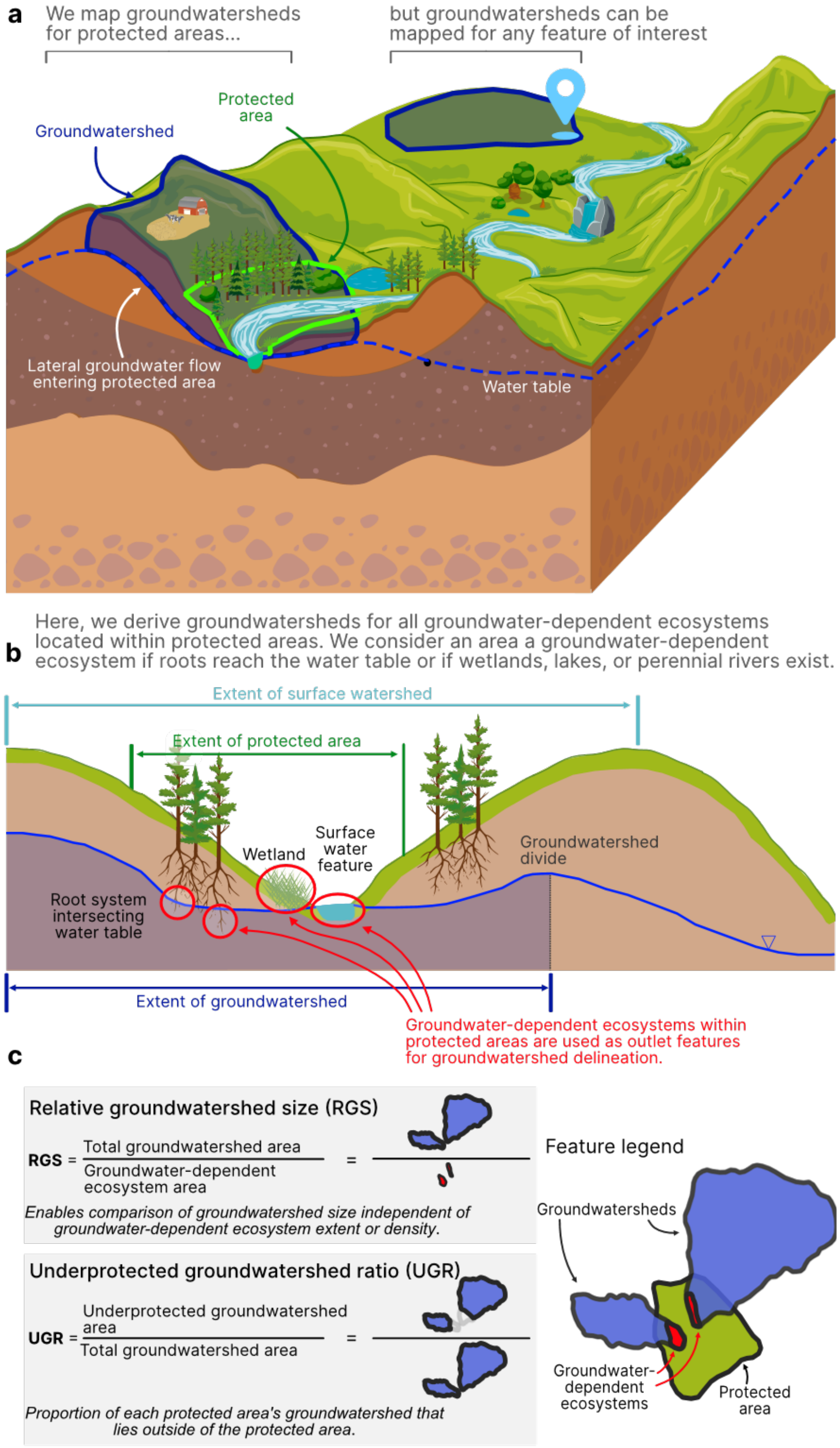


Fig. 2. Overview of groundwatersheds and our application of groundwatersheds in this study. (**a**) Conceptual model of groundwatersheds. (**b**) Mapping groundwatersheds for groundwater-dependent ecosystems within protected areas for a cross-section of panel a. (**c**) Metrics used to study patterns in groundwatersheds.

Results

Groundwatersheds of the world's protected areas

Groundwatersheds for protected areas are 84% larger (23.0 million km^2) than the combined size of the protected areas that we analyzed (12.6 million km^2), and over five in six groundwatersheds (85%) extend beyond their protected area boundary. Groundwatersheds also span international borders and raise transboundary management concerns: 484 groundwatersheds cross international borders despite their associated protected area existing entirely within a single country. Larger protected areas generally have larger groundwatersheds (Supplementary Fig. 2). Thus, patterns in total groundwatershed size largely reflect patterns in protected area size.

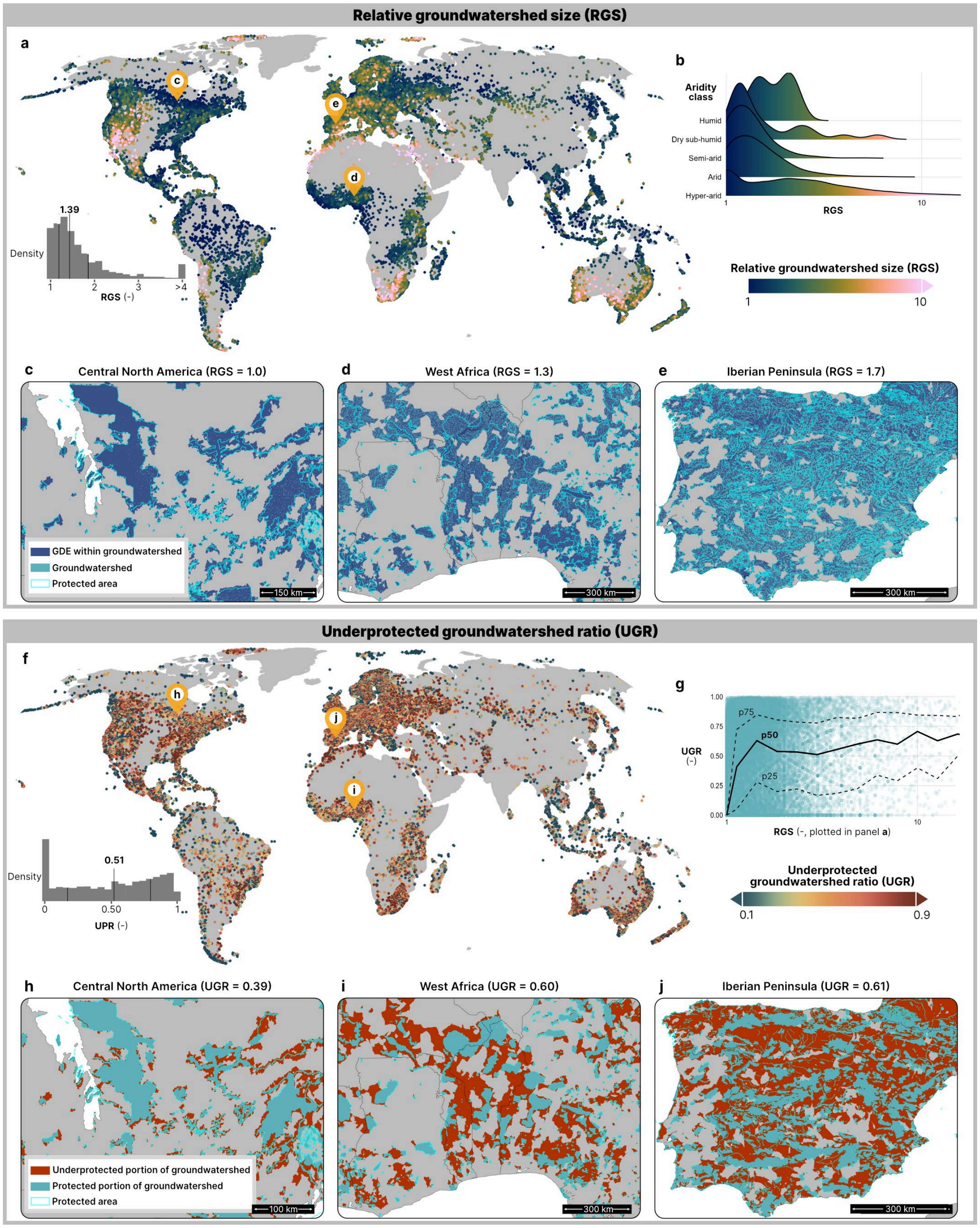
The median relative groundwatershed size (RGS) is 1.39 (Fig. 3a), with an interquartile range of 1.15 - 1.82. Overall, RGS tends to be larger in arid regions (Fig. 3b), which means that the size of contributing groundwater flow is greater in proportion to the size of the groundwater-dependent ecosystems they are connected to in arid regions in comparison to more humid regions. These larger RGS values in arid regions (e.g., Fig. 3e) are consistent with previous modeling of the impact of aridity on regional groundwater flow[35,36]. Larger RGS values in arid regions (e.g., Figure 2e) suggest that nested and regional flow paths are particularly important in these settings which are not represented in our water table-based approach (see Supplementary Information). Lower RGS values, as found in the boreal forest of central North America, correspond to groundwatersheds where vegetation is highly connected to shallower water tables. In these humid regions, convergence patterns in the water table are more localized, and lead to smaller shallow groundwatershed flow systems (e.g., Fig. 3c).

Trends in RGS do not differentiate a vulnerability gradient in protected areas but rather provide insights regarding the hydrogeological systems the protected areas depend on and provide context to inform protection strategies. That groundwatersheds exist outside of protected areas may appear as an intuitive finding, given that protected areas are rarely established on the basis of hydrological system boundaries or processes. Yet the global prevalence of this misalignment between protected areas and their groundwatersheds necessitates that these ecologically significant areas of contributing groundwater flow are considered by the conservation community when renewing goals and priorities across regional to global scales, and RGS is a metric to help inform and prioritize these efforts.

For instance, larger RGS generally imply that there is a larger area of contributing groundwater flow to manage. Further, larger groundwater flow systems generally have longer system response and residence times[37], meaning that human impacts in larger groundwatersheds may potentially have longer legacy impacts on GDEs than in smaller groundwatersheds. Conversely, protected areas with smaller RGS typically are in regions with a greater density of GDEs. Generally smaller groundwatershed sizes in these humid regions means that human impacts in these groundwatersheds may more rapidly transit to GDEs.

The median underprotected groundwatershed ratio (UGR) is 0.51 (Fig. 3f), with an interquartile range of 0.14 - 0.80. This means the median protected area's groundwatershed footprint exists 51% outside of the protected area boundary. The relationship between RGS and UGR (Fig. 3g) reveals that larger RGS leads to a larger UGR (i.e., a decreasing degree of protection). There are no regional trends visible in UGR however we do find that larger protected areas generally have lower UGRs in comparison to smaller protected areas (Supplementary Fig. 2), meaning that larger protected areas tend to have more-protected groundwatersheds.

UGR does not significantly vary with national levels of land protection (Supplementary Fig. 3). This result demonstrates that even in countries where international conservation targets have been met, or in jurisdictions where there is legislation directed at groundwater protection (such as the European Union Water Framework Directive), groundwatersheds of protected areas remain underprotected through conventional protected area initiatives. Combined, these findings reveal a global misalignment between protected areas and their connected groundwater flow systems and underscore the challenge of conserving protected area ecosystems above and below ground without consideration of groundwater flow.



Relative groundwatershed size (RGS)

c Central North America (RGS = 1.0)

d West Africa (RGS = 1.3)

e Iberian Peninsula (RGS = 1.7)

Underprotected groundwatershed ratio (UGR)

h Central North America (UGR = 0.39)

i West Africa (UGR = 0.60)

j Iberian Peninsula (UGR = 0.61)

Fig. 3. Mapping the groundwatersheds of the world's protected areas. (**a-e**) Relative groundwatershed size (RGS). (**a**) RGS of protected areas, plotted as points at the centroid of each protected area. (**b**) Distribution of RGS across aridity classes[38]. (**c-e**) Extent of groundwatersheds and groundwater-dependent ecosystems, which are the two inputs used to calculate RGS, shown for example regions in (**c**) central North America, (**d**) central West Africa, and (**e**) the Iberian Peninsula. (**f-j**) Underprotected groundwatershed ratio (UGR). (**f**) UGR of protected areas, plotted as points at the centroid of each protected area. (**g**) Relationship between RGS and UGR for all protected areas. (**h-j**) Extent of underprotected groundwatershed area and protected groundwatershed area, which are the inputs used to calculate UGR, shown for (**h**) central North America, (**i**) central West Africa, and (**j**) the Iberian Peninsula.

Human activity within underprotected groundwatersheds may undermine protection

Activities such as mining, agriculture, and urban expansion play a role in determining the potential risk to the quality and quantity of groundwater flow to protected areas. The degree of such human activity and land modification within underprotected portions of groundwatersheds represents a potential vulnerability for GDEs within protected areas (Fig. 4a). GDEs within protected areas could be affected directly by groundwater pumping and contamination, and indirectly via climate change or land use change through their impact on groundwater recharge [39–41]. The timing and severity of these impacts are a function of the type, location and magnitude of the activity in conjunction with the local hydrogeological setting. Assessing this timing and severity of impacts is beyond this study's scope but could enable improved management as we describe below.

Comparing patterns in human land modification[42] with UGR provides insight on the vulnerability of protected areas (Fig. 4b,c). To assess regional patterns, we summarized the level of land modification and UGR per terrestrial ecoregion. Ecoregions where we find high human modification levels and underprotected groundwatersheds are likely areas where groundwater-dependent ecosystems within protected areas are most vulnerable to potential impacts through groundwater flow. These ecoregions are scattered across the world and include: USA's Midwest to east coast, Central America, coastal Brazil, the majority of Europe, northern Africa, across the Sahel and Sudanian savanna in sub-Saharan Africa, Iran, Pakistan, and Northern India.

Groundwatershed coverage by other forms of protection

Herein, we have focused on higher levels of protection (IUCN protected area management categories I-III). However, expanding our analysis to include lower levels of protection (categories IV-VI) reveals that most groundwatersheds remain underprotected when considering lower levels of protection. The median national percentage of underprotected groundwatershed surface area (by high levels of protection) that is already protected by lower levels of protection is only 4%. However, Germany, Uruguay, Central African Republic, Myanmar, and South Korea are among a few nations whose lower levels of protected areas cover over 30% of the groundwatersheds that lie outside of their IUCN category I-III protected area (Supplementary Fig. 4). While expanding formal area-based protection of groundwatersheds is one approach for mitigating groundwater threats to a protected area that could contribute to the post-2020 Global Biodiversity Framework (Supplementary Fig. 5), that approach could be feasible or inappropriate in many contexts and may in fact be unnecessary if activities can be regulated through other means. Prioritizing groundwatersheds for protection would require additional information about timescales and magnitudes of impacts on the protected area.

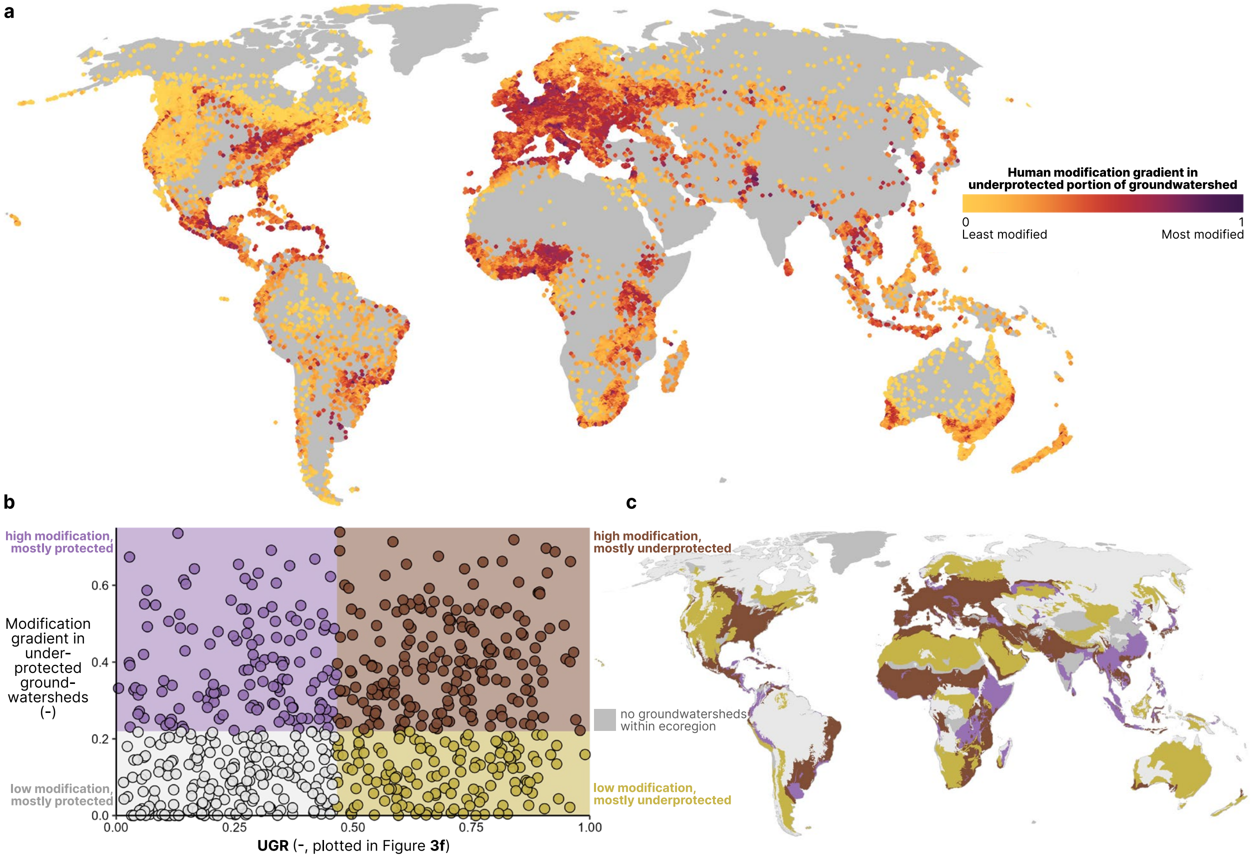


Fig. 4. Implications of groundwatersheds for conservation initiatives. (**a**) The human modification gradient of terrestrial lands[42] within the underprotected portions of protected area groundwatersheds. Protected areas with no underprotected groundwatershed area are not shown. (**b, c**) The relationship between UGR and the human modification gradient within underprotected portions of groundwatersheds, summarized per terrestrial ecoregions[43]. (**b**) A scatterplot of UGR and human modification gradient is split into four quadrants based on the median ecoregion value of each axis dimension. The colour scheme in the scatterplot doubles as the map legend for panel **c**. (**c**) The accompanying map corresponding to the four quadrants of panel b.

Discussion

Here, we have used groundwatersheds to reveal the global potential for distant and long-term subsurface impacts on groundwater-dependent ecosystems within protected areas. Yet, our mapping of groundwatersheds for protected areas is only one of many possible applications and this work can serve as a proof-of-concept for wider use. Groundwatersheds, like surface watersheds, can be identified for any feature (e.g., protected area, groundwater well, wetland of interest, city, etc.). The groundwatersheds concept has a strong potential to inform a range of decisions and management approaches for sustainability planning and resilience-building.

The variability of potential human impacts and the social, economic and political differences across regions implies that a diverse portfolio of approaches are necessary to protect groundwatershed water quality and quantity. Enhanced protection of groundwatersheds could be achieved through adoption or expansion of strategies such as groundwater regulation (e.g., well permitting), sustainable water policies (e.g., the Sustainable Groundwater Management Act in California, USA), source water protection (e.g., Edwards aquifer protection, in Texas, USA), Indigenous-led land and water management and monitoring (e.g., guardian programs such as northwestern Australia), conservation or regenerative agriculture (e.g., practices that reduce groundwater pumping), and nature-based solutions (e.g., invasive species removal for the Greater Cape Town water fund in South Africa). Management strategies could be borrowed or adapted from these and other conservation and source water protection approaches, rather than developing entirely new policy or management approaches. Selecting an appropriate strategy depends on the social, economic and political context as well as the degree of possible impacts, from severe (nearby, large magnitude pumping or contamination) to less impactful (distant or minor land use change).

While we focus on mapping the groundwatersheds of protected areas to place greater focus on groundwater in conservation initiatives, it is important to note that many protected areas also have surface watersheds extending beyond their boundaries. Directly comparing groundwatersheds with surface watersheds is non-trivial, as important differences exist in the conceptualization and analysis of these two different types of watersheds, and a detailed comparison is beyond our scope. In this study we included groundwater-dependent wetlands and root zone intersections to derive outlet locations for groundwatersheds, but these features are not typical outlet locations for surface watersheds. Furthermore, as surface watersheds are nested and hierarchical, their delineation also hinges on the spatial scale of study. For example, the surface watershed for Mangroves National Park in the Democratic Republic of Congo (located at the outlet of the Congo River) could range from a localized sub-basin to the entire Congo Basin, depending on the scale of analysis. Yet, it holds that for effective conservation, approaches must consider both contributing areas of groundwater and surface water flow that extend beyond protected area boundaries and the human impacts on these systems. For more discussion on comparing groundwatersheds to surface watersheds for protected areas, see the Supplementary Information and Supplementary Fig. 6.

Our results importantly highlight the connection between groundwater and protected areas and reveal the vulnerability of protected areas to potential groundwater impacts. However, our approach has limitations (see Supplementary Information). For instance, we used a simplified approach to identify potential groundwater-dependent ecosystems, focused on higher levels of protection, and mapped only the spatial extent but not the timing of human impacts acting on protected areas through groundwater flow. Thus, this first-order global analysis is not intended to lead to recommendations for specific protected areas but rather identifies regional trends in these relationships and discusses potential strategies. With more detailed information, our water-table based approach can be applied to smaller, specific areas. Alternatively, numerical models including particle tracking approaches that are computationally feasible at local scales can provide greater information about the full hydrogeological system and can produce critical insights when combined with the groundwatershed concept and motivation introduced here. As governments around the world commit to new protected area targets, and other actors make their own conservation commitments, our analysis serves as a reminder that protection does not stop at protected area borders nor at the ground surface.

Methods

We implemented a simple geospatial methodology using best-available, openly accessible global data (Supplementary Table 1) to map the groundwatersheds of the world's protected areas. The study approach is described in detail in the Supplementary Information. A flow chart of this study's methodology is shown in Supplementary Fig. 7. All analyses in this study were performed at the spatial resolution of 30 arc-second grid cells (~1 km at the equator), matching the resolution of the core global water table data used in this study. See the Supplementary Information for a discussion on the implications of performing all analysis at this spatial resolution.

A computationally simple approach to groundwatershed mapping

Groundwatersheds were derived by making minor modifications to the D8 surface watershed delineation method[44]. Whereas surface watersheds are derived using an outlet location (or 'pour point') and a digital elevation model of the land surface, groundwatersheds are derived using potentially multiple outlet locations and the water table surface instead of the land surface. Whereas a surface watershed identifies the contributing area of overland flow to a point of interest, a groundwatershed identifies the contributing area of local groundwater flow to groundwater-connected features of interest. In this study, these features of interest are groundwater-dependent ecosystems within protected areas.

Using this water table-driven D8 flow direction algorithm to derive groundwatersheds does not enable representation of nested, deeper, regional groundwater flow systems (Supplementary Fig. 6). For a full discussion on our justification of our approach and its limitations, see the Supplementary Information. In the following sections, we summarize our methods to identify groundwater-dependent ecosystems and protected areas, which are combined to derive groundwatershed outlet locations.

Water table

The water table depth data contains two data sets: mean monthly water table depths and mean annual water table depth, both averaged over a 10-year model run as documented in Fan et al.[24]. As water table elevations, not water table depths below the land surface, drive local groundwater flow, we converted water table depth to water table elevation by subtracting water table depth from the land surface elevation. We used mean monthly water table elevations in our derivation of groundwater-dependent ecosystems and in our groundwatershed uncertainty analysis and we used the mean annual water table in our core groundwatershed delineation.

Groundwater-dependent ecosystems

Though we mapped the groundwatersheds of the world's protected areas, we did not map groundwatersheds using the entire extent of protected areas as outlet features. Rather, we identified and used areas within the protected areas where there are likely groundwater-dependent ecosystems (GDEs). To identify GDEs, we considered ecosystems reliant on surficial (e.g., wetlands, rivers) and subsurface (e.g., phreatophytes) expressions of groundwater, but not subterranean (e.g., hyporheic, karst)[45]. GDEs were mapped globally using an inference-based approach based on the following: (i) the interaction between rooting depths and the depth to the water table (terrestrial GDEs), (ii) the presence of groundwater-dependent wetlands (lentic aquatic GDEs), and (iii) surface water systems interconnected with groundwater (lotic aquatic GDEs) systems. Together, these interactions connect groundwater to terrestrial and aquatic ecosystems and are represented by available global data. Our process to identify these interactions is summarized in the numbered paragraphs below.

1) To identify likely terrestrial GDEs, we considered the relationship between rooting depth and depth to the water table. We identified grid cells where root systems are likely sourcing groundwater by comparing mean monthly depths to the water table[24] with the depth to the bottom of the root zone[25]. Any grid cell in which the root zone intersects the water table for at least one month per year is identified as a terrestrial GDE.

2) To identify likely aquatic GDEs, we considered multiple forms of groundwater-surface water interactions and classified aquatic GDEs as either lotic or lentic systems. To identify lentic systems, we used existing binary maps of groundwater-dependent wetlands[23] and lake extents[27].

3) To identify lotic (riverine) aquatic GDEs, we used a network of perennial rivers[26]. Though not all rivers and surface water bodies depend on groundwater discharge (e.g., disconnected river reaches), global data availability does not permit the consideration of these hydrologically disconnected surface water bodies. However, our use of only perennial river reaches minimizes this impact. We also do not remove losing river and stream reaches as surrounding water table levels regulate the hydraulic gradient across groundwater-surface water interactions. Losing stream reaches can be reflected in our analysis by lower surrounding water table levels and thus will not receive an associated contributing groundwatershed beyond the groundwater-dependent ecosystem grid cell(s). In particular, intermittent rivers with a seasonal interconnection between the groundwater and surface water system (i.e., gaining during the wet season, losing during the dry season)[46] may be sensitive to changes in seasonal groundwater levels, but may have been missed in our analysis that focuses on mean annual conditions.

We then combined these three GDE types (i.e., terrestrial, lotic and lentic) into a single GDE map. Among these GDEs, those that are located within protected areas (see below) are used as outlet features in our groundwatershed delineation.

Protected area preparation

From the World Database on Protected Areas[28], we subset two groups of IUCN terrestrial protected area categories: those with high degrees of protection that restrict human activity within their boundaries, and those with lower degrees of protection that are more permissive of human activity. The protected area classes we considered as highly protective were: Ia (Strict Nature Reserve), Ib (Wilderness Area), II (National Park), III (National Monument or Feature), as well as protected areas with “Not Reported” or “Not Assigned” categories. We included “Not Reported” and “Not Assigned” protected areas in this high protection class as we found these categories to be more prevalent in the countries with lower levels of development where reporting of protected areas may be less comprehensive. By including these categories, we retained a greater global coverage within the protected areas data set. The remaining protected area categories: IV (Habitat/Species Management Area), V (Protected Landscape/Seascape), VI (Protected area with sustainable use of natural resources), and “Not Applicable”, are grouped into a class representing lower levels of protection.

We rasterized both sets of protected area classes to our operating resolution, including all grid cells touching a protected area. As the spatial resolution of our analysis is 30 arc-seconds (~1 km), we filtered out any protected areas with a reported surface area less than 1 km^2 before rasterization. As protected areas can overlap or border one another, we subsequently identified all spatially contiguous protected areas once representing the protected areas in binary, 30 arc-second raster format. To correct for any protected area fragmentation during rasterization, we also filtered out any protected areas with a calculated surface area less than 1 km^2 after rasterization. This set of spatially contiguous protected areas is the protected area set we use as the basis for all calculated metrics (i.e., the relative groundwatershed size and the underprotected groundwatershed ratio) and to report summary statistics.

Using this spatially contiguous but flattened representation of protected areas enabled a more streamlined approach to handle and report global protected area results. However, these contiguous protected areas differ in total count from the original protected area dataset from which they are derived.

Groundwatershed delineation

Our groundwatershed delineation process followed conventional watershed delineation approaches that generate a flow direction raster which is used to derive watersheds for specified features. We did not apply additional hydrological preconditioning steps to the water table surface, such as the removal of depressions as depressions in the water table represent local water table gradients which we sought to represent in our study. The flow direction raster was generated using the D8 flow direction method which can represent 8 possible flow directions to adjacent cells according to the direction of the steepest water table gradient. Though the D8 algorithm has known limitations, such as generating parallel flow paths and poorly depicting watersheds in coastal and endorheic basins[47,48], it remains a common, simple, deterministic and widely used approach to derive flow direction. Secondly, improving the sophistication of our flow direction derivation may be unwarranted as our analysis was performed at a coarse spatial resolution (30 arc-second) which is much coarser than conventional watershed-specific delineation studies.

Once the flow direction raster was generated, groundwatersheds were delineated for each GDE cell found within a protected area. Subsequently, groundwatersheds for individual GDE grid cells were aggregated across all GDEs found in each contiguous protected area. To avoid double-counting of groundwatershed area, we assign a single groundwatershed per protected area even if groundwatershed extents may overlap between protected areas. This is possible when a protected area is found within the groundwatershed of another protected area's groundwatershed (visualized in Supplementary Fig. 8). In these cases, the groundwatershed area for the nested protected area is assigned to this protected area, while the remaining groundwatershed area is assigned as the groundwatershed for the downgradient protected area. For a discussion on how this methodological decision affects our calculated summary metrics (i.e., the relative groundwatershed size, RGS; and the underprotected groundwatershed ratio, UGR), see the Supplementary Information. For flow direction raster and groundwatershed delineation steps, we used the 'D8Pointer' and 'Watershed' functions in the Hydrological Analysis toolbox of the open source geospatial platform Whitebox Geospatial[49].

Relative groundwatershed size (RGS) and Underprotected groundwatershed ratio (UGR)

Once groundwatersheds were delineated for each contiguous protected area, we subsequently evaluated the two metrics developed to understand regional patterns in groundwatersheds. Relative groundwatershed size (RGS) is calculated by dividing the surface area of each groundwatershed by the surface area of groundwater-dependent ecosystems found within the groundwatershed. Importantly, we also consider GDE surface area that exists outside of the protected area but is within the groundwatershed as stopping at the protected area boundary introduces a social influence on the ecohydrological metric. The underprotected groundwatershed ratio (UGR) is calculated by dividing the surface area of the groundwatershed that lies outside of the protected area by the total surface area of the groundwatershed. These metrics are summarized in Supplementary Table 2.

Uncertainty analysis

As groundwatersheds are dynamic (i.e., fluctuate with the water table) we performed an uncertainty analysis to quantify the degree to which the extents of groundwatersheds change throughout a typical year. To accomplish this, we repeated our groundwatershed delineation process for mean monthly water table depths and evaluated the variability in total groundwatershed size throughout a year. The results of this uncertainty analysis are included in the Supplementary Information and Supplementary Figs. 9 and 10.

We also performed a rudimentary analysis to demonstrate the potential and challenges of replicating this study for surface watersheds. This analysis is described in detail in the Supplementary Information.

Data availability

Source data are documented in Supplementary Table 1 and can be downloaded from the persistent web-links provided. Data produced in this study will be uploaded to an open-access repository upon manuscript acceptance.

Code availability

Code used to produce all results in this study is available at https://github.com/XanderHuggins/groundwatersheds-for-PAs. All analyses were conducted using the R project for statistical computing[50]. R packages necessary for analysis and visualization include: terra[51], gdalUtilities[52], rasterDT[53], whitebox[54], ggplot2[55], tmap[56], scico[57,58], and MetBrewer[59]. Composite figures were assembled in Affinity Designer (https://affinity.serif.com/en-us/designer/).

Supplementary information

A supplementary information file is available.

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Figure 2 was produced by the authors with support from Liley Bueno and Sergio Lopez by modifying: vector graphics from artist ‘brgxfx’, accessed on the graphic repository Freepik (www.freepik.com); vector graphics from artists Tracey Saxby and Jason C. Fisher, accessed on the Integration and Application Network (ian.umces.edu/media-library); and a vector graphic from artist Adrien Coquet, accessed on The Noun Project (thenounproject.com).

Author contributions statement

The study was conceived by S.Z., T.G. A.H., and F.J. The methods were developed by T.G., X.H., S.Z., A.H., F.J., and D.S. Analysis was performed by X.H. Figures were developed by X.H., T.G., and D.S. Manuscript writing was led by X.H., T.G., and D.S. with input from all authors. All authors, X.H., T.G., S.Z., D.S., M.M.R., K.V., R.A., A.H., and F.J., discussed results and edited the manuscript at multiple stages.

Competing interests statement

The authors declare no competing interests.