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Overlooked risks and opportunities for global protected areas revealed by mapping groundwatersheds

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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, a groundwater-modified watershed delineation. We find that most groundwatersheds (83%) of the world’s protected areas are partially unprotected and are overall only 52% protected by surface area. These findings highlight a widespread potential risk to protected areas if activities affecting groundwater are uncontrolled within their groundwatersheds, underscoring the need for groundwatershed-focused protection measures. Delineating groundwatersheds can catalyze

needed discussions about protected area connectivity and effectiveness, and investments in groundwatershed conservation and management that can help ensure groundwater-dependent ecosystems are uncompromised by avoidable external underground threats.

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 land protections have had clear limitations in regard to conserving freshwater ecosystems and species, which have shown staggering declines[6,7]. One often-cited reason for this inefficacy is the lack of protection for hydrologically connected freshwater systems outside (i.e., upstream and downstream) of protected areas[8,9]. With the development of the Convention on Biological Diversity's Post-2020 Global Biodiversity Framework[10], members of the conservation community have advocated for expansion of the network of protected areas to cover 30% of terrestrial, inland water, and sea areas by 2030[11]. The draft '30x30' target goes beyond coverage to also include management effectiveness, yet the need to manage human activities in connected lands and waters outside protected areas is absent from effectiveness discussions and indicators[12]. Examples of iconic protected areas like Doñana National Park[13] and Grand Canyon National Park[14] illustrate how impacts from activities such as agricultural drainage, mining, and groundwater pumping can affect internal protected area processes and compromise protection effectiveness.

As human land and water use intensifies around many protected areas[2,15], the management of surrounding groundwater becomes increasingly important. No systematic study has investigated the potential for human activities outside of protected areas to have impacts on protected areas through groundwater flow (Figure 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]. Aquatic ecosystems can also be threatened by human activities transmitted through groundwater flow. Groundwater pumping, for instance, can reduce streamflow and drive streams from perennial to intermittent, ephemeral, or even disconnected[19–23]. In addition, since groundwater provides distinct chemical and temperature attributes and can transmit contaminants such as nutrients[24], changes in groundwater levels and flow can introduce pollutants or otherwise alter water quality in protected areas[25].

In this study, we estimate the area from which human impacts may propagate via groundwater flow to protected areas. We employ a generic, reproducible workflow to derive groundwatersheds (Box 1 and Supplementary Information) and apply this methodology to (i) map and identify the groundwatersheds of the world's protected areas; (ii) assess physical controls on the size of groundwatersheds; and (iii) identify risks to existing protected areas and opportunities for improved conservation outcomes. By developing and applying the groundwatershed concept, we reveal areas contributing localized groundwater flow to the world's protected areas.

Box 1: What are groundwatersheds?

Groundwatersheds are the area from which localized groundwater systems flow to a feature (Figure 1). Groundwatersheds are similar to surface watersheds, which are derived based on the topography of the land surface. Instead, groundwatersheds are derived from the topography of the water table. While the water table is generally understood as a subdued replica of the land surface topography, this assumption is not uniformly valid[26]. Thus, the contributing groundwatershed and surface watershed can be spatially misaligned for the same draining feature[27]. Groundwatersheds, like surface watersheds, can be identified for any feature (e.g., protected area, city, individual well, etc.) but unlike watersheds defined by static topography, groundwatersheds are dynamic in that their size and shape can change with the water table due to pumping, climate change, land use change, or seasonality. Therefore, groundwatersheds can be affected by a multitude of natural and human factors including aridity, infiltration capacity, recharge, evaporation rates, and land use. However, we expect the majority of each mapped groundwatershed to be static because fluctuations in the water table will only correspond to changes in the groundwatershed extent if the location of divergent water table slopes are altered. We believe the groundwatershed concept was first introduced by Haitjema[28] to evaluate groundwater residence times, and similar concepts have been called *groundwater catchments*[29], *groundwater basins*[30], and mapping of *groundwater divides*[31]. However, the concept has seen limited uptake in water science and management likely because groundwater is often an overlooked resource. Mapping the groundwatersheds of protected areas is only one of many possible applications and therefore this work can serve as a proof-of-concept for wider application of groundwatersheds to inform a range of decisions, such as protecting drinking water sources.

In our parsimonious approach to derive groundwatersheds, it is only necessary to have a spatially distributed representation of the water table and the spatial location or extent of the feature(s) whose groundwatershed is to be determined. For this study, we rely on seven core global data sources to map groundwatersheds: a global database of protected areas[32], a depth to water table map[33], a maximum rooting depth map[34], the water table and rooting depth studies' associated land surface digital elevation model, a map of groundwater-driven wetlands[35], a map of surface water bodies[36], and a line network of perennial rivers[37]. We identify locations where groundwater is likely connected to terrestrial or aquatic ecosystems (herein called 'ecologically connected areas') if an area satisfies one of four possible criteria: if the root zone intersects the water table for at least one month per year, or if there exists a groundwater-driven wetland, perennial stream, or surface water body. This approach can be considered a globally consistent but rudimentary mapping of groundwater-dependent terrestrial and aquatic ecosystems, although we do not include subsurface ecosystems explicitly[38]. We then use these identified locations within protected areas as 'outlets' for a watershed delineation algorithm using the water table surface in replacement of the land surface. Finally, we identify groundwatersheds for each protected area by spatially joining groundwatersheds for all ecologically connected areas within each protected area (see Methods).

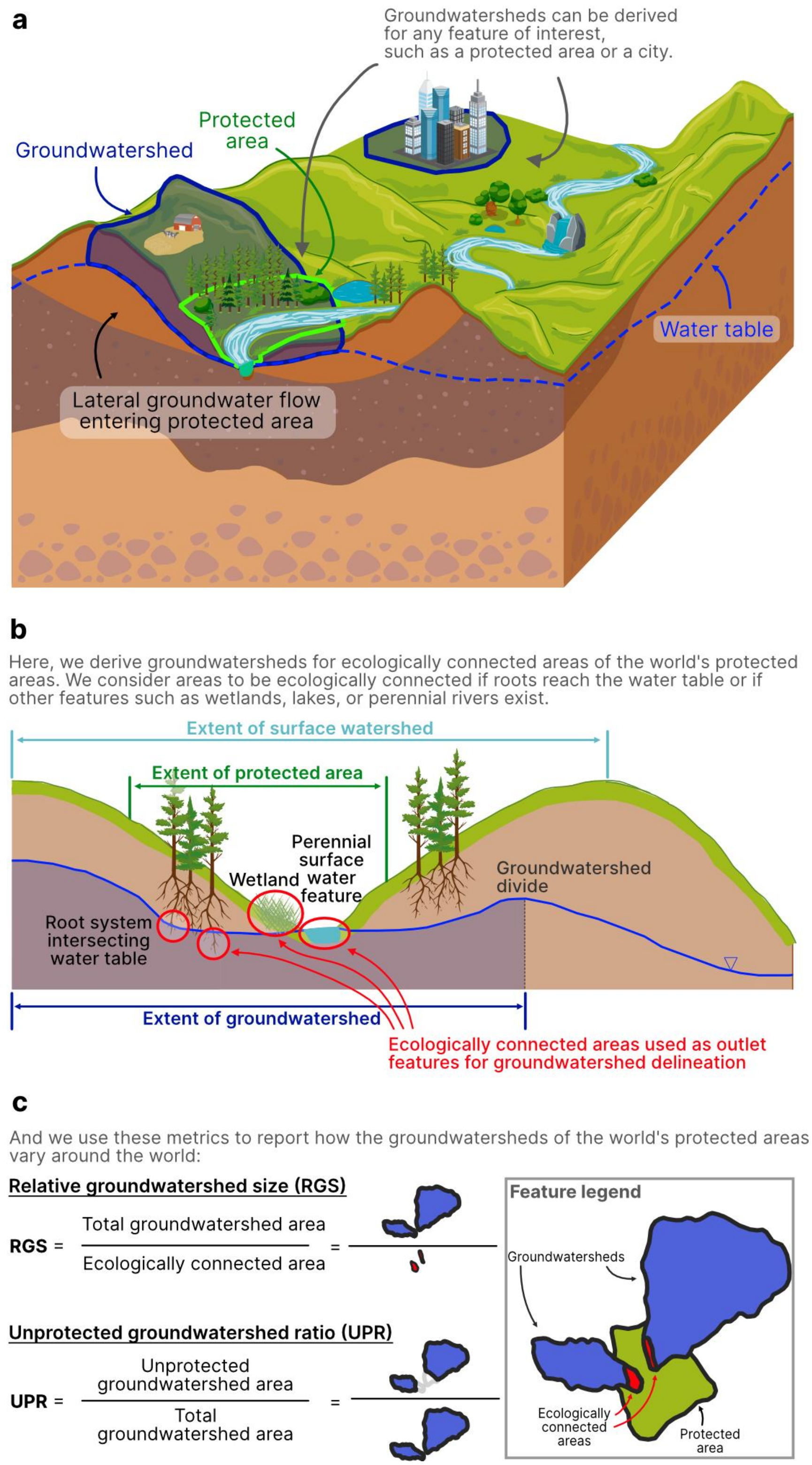

Figure 1. Overview of the groundwatersheds concept, and our application of the concept in this study. (**a**) Conceptual model of groundwatersheds for features of interest across a landscape. (**b**) Mapping groundwatersheds of ecologically connected features within a protected area. (**c**) Metrics to study controls and potential impacts for groundwatersheds.

Results

Groundwatersheds of the world's protected areas

Groundwatersheds for protected areas are 83% larger (23.1 million km^2) than the combined size of the protected areas around the world that we considered (12.6 million km^2; Supplementary Figure 3). Almost all groundwatersheds extend beyond protected area boundaries. Specifically, across all protected areas with an associated groundwatershed, 83% (~31,200 of ~37,400 spatially contiguous sets of protected areas) have some proportion of their groundwatershed unprotected. This corresponds to 71% of all protected areas globally, as 14% of protected areas did not have an associated groundwatershed. A protected area has no associated groundwatershed when no 'ecologically connected areas' are identified within the protected area (see Box 1). Potential cross-boundary impacts of protected areas are large as overall protected areas only encompass 52% of their own groundwatersheds by area. Groundwatersheds also span international boundaries and raise transboundary management concerns: 494 groundwatersheds cross international borders despite their associated protected area existing entirely within a single country.

To evaluate the potential importance of groundwatersheds and analyze their relationship with protected areas globally, we defined two metrics (Figure 1c): relative groundwatershed size (RGS) and the unprotected groundwatershed ratio (UPR). RGS is an ecohydrological index representing size of the groundwatershed relative to the ecologically connected area within the groundwatershed (Figure 2a). UPR is a socio-hydrological conservation index that represents the unprotected proportion of each groundwatershed (Figure 2f). Overall, groundwatersheds tend to be larger in arid regions (Fig 2b) which is consistent with previous modeling of the impact of aridity on regional groundwater flow[39,40]. Lower RGS values (e.g., as found in the boreal forest of central North America) correspond to groundwatersheds where vegetation is highly connected to the water table. In these humid (low aridity) regions, shallow water tables constrain groundwatershed size (Figure 2b). Conversely, groundwatersheds with high RGS values (e.g., central Sahel and western African, and the Iberian Peninsula) tend to be located in more arid regions. Larger groundwatersheds in arid regions suggest groundwater flow is of heightened importance for conservation initiatives in these regions.

The relationship between RGS and UPR implies that increasing relative groundwatershed size is related to a decreasing degree of protection (Figure 2g). UPR does not significantly vary with the percentage of national land area protected (Supplementary Figure 4a), implying that even in countries where conservation targets have been met or where there is legislation directed at groundwater protection (such as Figure 2j with the EU Water Framework Directive), groundwatersheds often remain unprotected through conventional protected areas. Further, we find no relationship between UPR and subnational GDP per capita (Supplementary Figure 4b), implying that increasing national wealth does not lead to increased groundwatershed protection through formally designated areas. This partially echoes findings that greater increases in effective conservation extents are needed in developed economies than in developing economies to safeguard biodiversity[41]. These possibly counterintuitive findings that groundwatersheds may not be better protected in wealthier countries or in countries with greater protected area coverage suggests a global misalignment between protected areas and their connected groundwater flow systems and underscores the challenge of conserving protected area ecosystems above and below ground without consideration of groundwater flow.

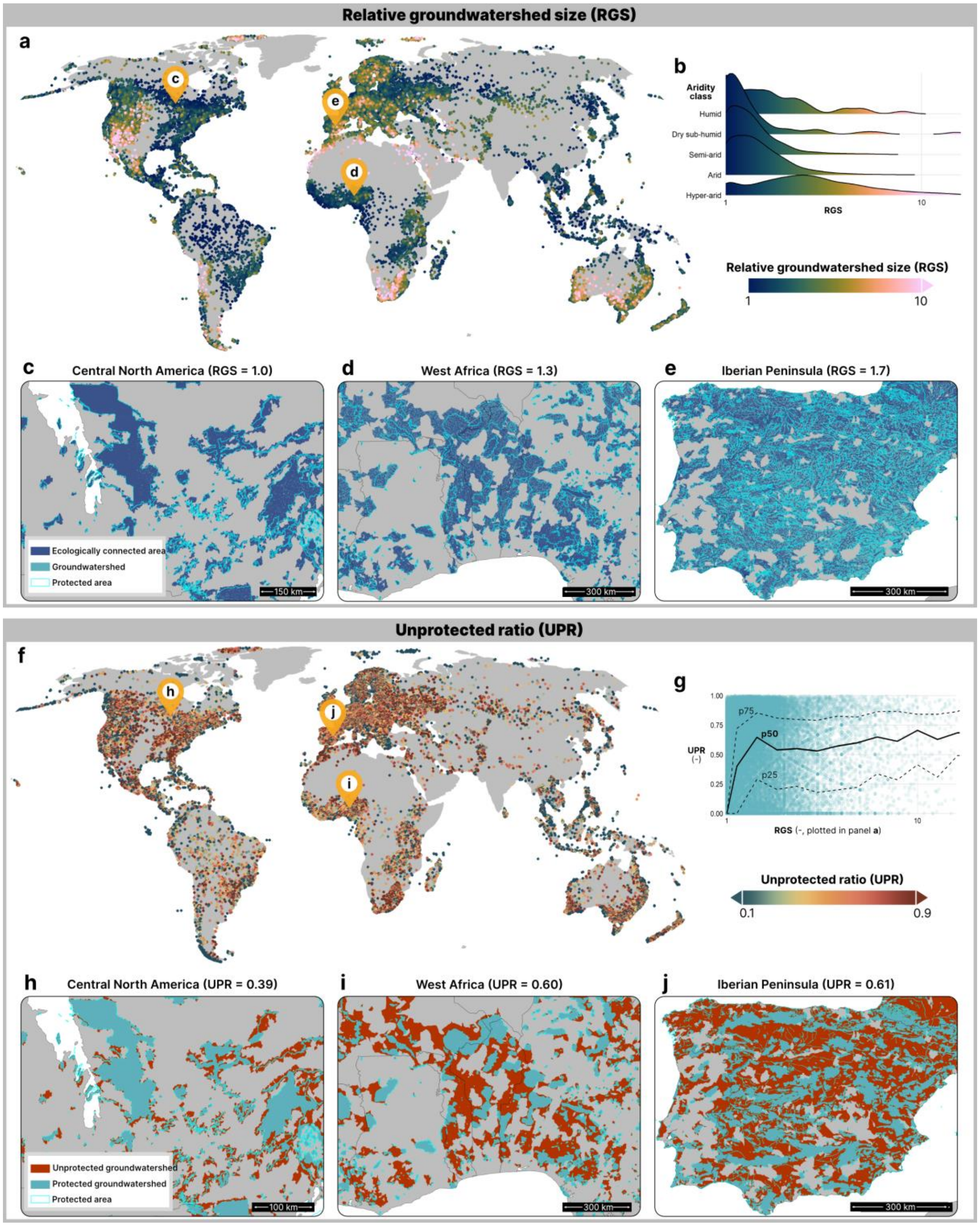

Figure 2. Mapping the groundwatersheds of the world's protected areas. (**a-e**) Relative groundwatershed size (RGS). (**a**) RGS of protected areas, plotted as a point at the centroid of each protected area. (**b**) Distribution of RGS across aridity classes. (**c-e**) Extent of groundwatersheds and ecologically connected areas, which are the two inputs used to calculate RGS, shown for (**c**) central North America, (**d**) central West Africa, and (**e**) the Iberian Peninsula. (**f-j**) Unprotected ratio (UPR). (**f**) UPR of protected areas, plotted as a point at the centroid of each protected area. (**g**) Relationship between RGS and UPR for all protected areas. (**h-j**) Extent of unprotected groundwatershed area and protected groundwatershed area, which

are the inputs used to calculate UPR, shown for (**h**) central North America, (**i**) central West Africa, and (**j**) the Iberian Peninsula.

Degree of human activity within groundwatersheds

The concept and application of groundwatersheds reveals potential long-range and long-term subsurface impacts on features of interest. Activities such as mining, agriculture, and urban expansion, captured in the human modification gradient[42] (Figure 3a), play a role in determining the potential risk to the quality and quantity of groundwater flow to protected areas. Conceptually, the potential vulnerability of protected areas can be represented by the human modification gradient within unprotection portions of their groundwatersheds (Figure 3b). Specifically, ecologically connected areas within protected areas could be affected most directly by groundwater pumping and contamination, and indirectly via land use or climate change through, for instance, changes to groundwater recharge. The timing and severity of these cumulative impacts would be a function of the type, location and magnitude of the specific stressor, which is beyond this study's scope, but could enable improved management as we describe below.

Overall, we see considerable variability in both UPR and the modification gradient for both individual protected areas and when summarized to terrestrial ecoregions of the world (Figure 3b). Regions of greatest concern, where we find high human modification gradients within predominantly unprotected groundwatersheds (i.e., protected areas with high UPR values), include the Midwest to east coast of the USA, across the British Isles and Europe, Western Africa, Northern India, Pakistan, and the east coast of Brazil (Figure 3c).

Groundwatershed coverage by lower levels 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 while most groundwatersheds remain unprotected when considering lower levels of protection, there are a small set of nations whose lower levels of protected areas encompass significant proportions of the groundwatershed we have mapped. The median national percentage of unprotected 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 Figure 5). 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 Figure 6), 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.

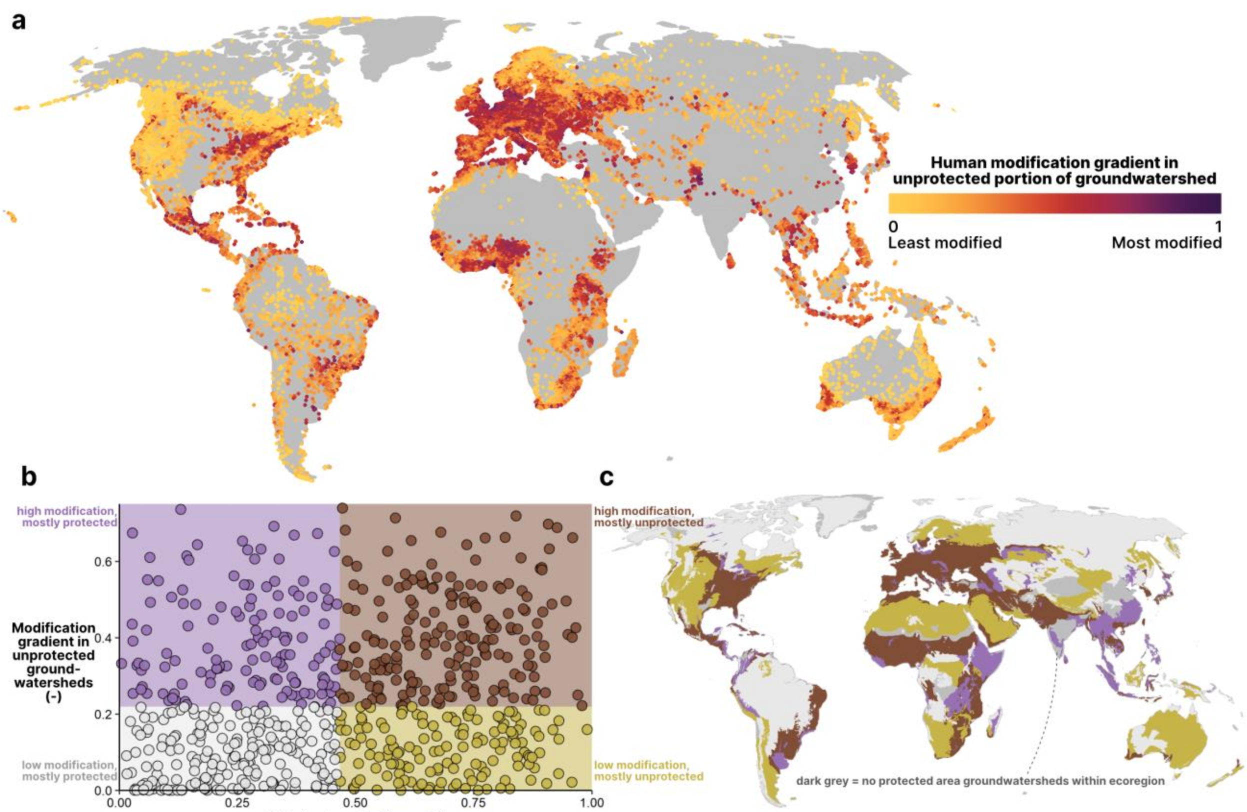

Figure 3. Implications of groundwatersheds on conservation initiatives. (**a**) The human modification gradient within the unprotected portion of groundwatersheds for global protected areas. Protected areas with no unprotected groundwatershed area are not shown. (**b, c**) The

relationship between UPR and the human modification gradient within unprotected portions of groundwatersheds, summarized across the terrestrial ecoregions of the world[43]. (**b**) A scatterplot of UPR against modification gradient split into quadrants based on median ecoregion values of each axis dimension, which corresponds to the color scheme of the mapped ecoregions in (**c**).

Discussion

The variability of potential human impacts and the social, economic and political differences across regions implies a portfolio of approaches are available for protecting groundwatershed water quality and quantity, in addition to formal protected areas. Enhanced protection of groundwatersheds could be achieved through strategies such as groundwater regulation (e.g., well permitting), sustainable water policies (e.g., 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).

Our results importantly 'daylight' the connection between groundwater and protected areas and highlight 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 (IUCN protected area categories I-III), and mapped only the possible spatial extent but not the timing of groundwatershed-protected area connections. Thus, this first-order global analysis is not intended to lead to recommendations for specific protected areas but rather explores global trends in these relationships and possible strategies. As governments around the world commit to new protected area targets, and other actors like companies make their own conservation commitments, our analysis can serve as a reminder that protection stops neither at protected area borders nor at the ground surface. The concept of groundwatersheds, equally applicable to any groundwater-connected feature, has strong potential with further refinement to inform sustainability planning and resilience-building around the world.

Methods

We sought to implement a simple geospatial methodology using best-available, openly accessible global data to map the groundwatersheds of the world's protected areas. The study approach is described in detail in Supplementary Section 1. All data used in this study were obtained from published, open-access data sets and are described in Supplementary Table 1. A flow chart of this study's methodology is shown in Supplementary Figure 1. All analyses in this study were performed at 30 arc-second resolution (~1 km at the equator).

A computationally simple approach to groundwatershed mapping

Groundwatersheds were derived by making minor modifications to a conventional surface watershed delineation method. 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 an outlet location and the water table 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 a feature of interest. Our methodology does not identify contributing areas of subregional and regional groundwater flow, as discussed in study limitations (see Supplementary Information) and as shown in Supplementary Figure 2. In the following sections, we summarize our methods to identify groundwatershed outlet locations and to derive groundwatersheds.

Groundwatershed outlet preparation

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 required for groundwatershed delineation, we converted water table depth to water table elevation by subtracting water table depth from the land surface elevation. We used the mean monthly water table elevation data in our derivation of ecologically connected areas and in our groundwatershed uncertainty analysis and the overall mean water table elevation data in our core groundwatershed delineation.

Root zone: Similar to water table depth, we converted rooting depth to rooting elevation by subtracting rooting depth from the land surface elevation. This elevation represents the elevation of the bottom of the root zone. This rooting zone elevation is used in the derivation of ecologically connected areas.

Protected areas: From the World Database on Protected Areas (see Supplementary Table 1), we subset two groups of protected area categories: those with relatively high degrees of protection and those with lower degrees of protection. We considered IUCN terrestrial protected area categories: 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 as areas with high degrees of protection. We included “Not Reported” and “Not Assigned” protected areas in this high protection class following a UNEP recommendation and as we found these categories to be more prevalent in the Global South 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.

With these two simplified protected area classes, we rasterized both sets to our operating resolution, including all grid cells touched by a protected area. As the grain of our analysis is 30 arc-seconds (~1 km), we additionally filtered out any protected areas with a reported surface area <1 km^2 before rasterization. Lastly, we identified all spatially contiguous protected areas, which we used as the protected area layer to calculate our derived metrics (see Box 1) and report summary statistics. We opted to identify contiguous protected areas rather than use the unique identities of individual protected areas as some protected areas overlap or abut one another. Using this spatially contiguous but flattened representation of protected areas provided 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. We primarily used the “high level of protection” class of protected areas in our analysis. The “low level of protection” class was used in our post-hoc analysis.

Ecologically connected areas: Though we sought to identify the groundwatersheds of the world’s protected areas, we opted not to delineate groundwatersheds using the entire extent of protected areas as outlet features. Rather, we identified and used areas within the protected areas where it is reasonable to assume there are interactions with groundwater. To identify such areas, which we refer to as “ecologically connected areas”, we considered: (i) the interaction between rooting depths and the water table, (ii) the intermittency of rivers, (iii) the presence of groundwater-related wetlands, and (iv) other surface water bodies. These considerations, together, represent various mechanisms that link groundwater to surface processes, including root water uptake and groundwater-surface water interactions.

We identified areas where root systems are likely sourcing groundwater by comparing mean monthly water table elevations with the elevation of the bottom of the root zone. We considered any grid cell in which the root zone intersects the water table for at least one month per year as an ecological connection. We then identified areas where groundwater-surface water interactions are likely to occur. We did so by considering the location of perennial rivers, groundwater-related wetlands, and lake extents. The combination of these locations: where root zones intersect the water table, where groundwater-related wetlands exist, and where groundwater-surface water interactions are likely to occur represent the ‘ecologically connected areas’ we used as outlets in our groundwatershed delineation. Though not all rivers and surface water bodies depend on groundwater discharge (e.g., losing river reaches), these are reflected by lower surrounding water table levels and thus will not receive an associated contributing groundwatershed beyond the ecologically connected cell(s). As we are only concerned with identifying the groundwatersheds of protected areas, our final preparation step was to mask all ecologically connected cells to the extent of protected areas before use in the groundwater delineation process.

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. However, and as aforementioned, we substituted the derived water table surface for the land surface elevation when deriving the flow direction raster. 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, it remains a common, simple, and widely used approach to derive flow direction. Secondly, improving the sophistication of our flow direction derivation may not be warranted as our analysis was performed at a coarse spatial resolution (30 arc-second), which is much coarser than watershed-specific delineation studies that are often conducted at <100 m resolution.

The groundwater flow direction raster was used to derive groundwatersheds in combination with the derived ecologically connected cells. Each ecologically connected cell was converted to a spatial point file at the centroid of the grid cell. Each point was used as a 'pour point' in the watershed delineation algorithm. Once groundwatersheds were derived for individual pour points, they were merged based on their associated contiguous protected area. For flow direction raster and groundwatershed delineation steps, we used the 'D8Pointer' and 'Watershed' tools in the Hydrological Analysis toolbox of the open source geospatial platform Whitebox Geospatial[44].

Uncertainty analysis

As groundwatersheds are dynamic (i.e., can 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. For this, we used mean monthly water table depths rather than the mean annual water table depth and repeated our groundwatershed delineation process for all months. While we observed month-to-month variation in groundwatershed extent across most groundwatersheds, we found that the total area of groundwatersheds for the world's protected areas fluctuates little throughout the year (Supplementary Figures 7, 8). These small fluctuations in total groundwatershed size indicate the robustness of our first-order analysis of global groundwatershed mapping. However, these uncertainty results simultaneously underscore the need for methodological advances to map groundwatersheds using improved process representation in future studies to refine these estimates and allow for consideration of regional and complex groundwater flow systems.

Data availability

Source data are documented in Supplementary Table 1 and can be downloaded from the persistent web-links provided. Groundwatershed 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. This repository will be archived on a dedicated archiving service (such as Zenodo) upon manuscript acceptance. All analyses were conducted using the R project for statistical computing[45]. R packages necessary for analysis and visualization include: terra[46], gdalUtilities[47], rasterDT[48], whitebox[44,49], ggplot2[50], tmap[51], scico[52,53], and MetBrewer[54]. Composite figures were assembled in Affinity Designer (https://affinity.serif.com/en-us/designer/).

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The study was conceived by T.G. A.H., S.Z., 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., D.S., and F.J. Figures were developed by X.H., T.G., and D.S. All authors, D.S., X.H., T.G., S.Z., 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 that they have no competing interests.