

Catchment landforms predict groundwater-dependent wetland sensitivity to recharge changes

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Abstract. This study investigates the influence of topography on the desaturation rates of groundwater-dependent wetlands in response to changes in recharge. We examined ~~sixty~~60 catchments across northern Chile, which feature a wide variety of landforms. ~~We categorized the landforms~~Landforms were categorized using geomorphon descriptors, ~~identifying resulting in~~ three distinct clusters: ~~lowlandflat~~, ~~transitionintermediate~~transitional, and mountain settings. Using steady-state 3D groundwater models, we derived flow partitioning and seepage area extent for each catchment. Each cluster ~~revealed-exhibited~~ consistent seepage areas evolution under varying wet-to-dry conditions. Our findings indicate that mountains ~~exhibit-have~~ reduced seepage area compared to ~~lowlands-flats~~ at equivalent hydraulic conductivity to recharge (K/R) ratios, but are less sensitive to recharge fluctuations, with slower rates of seepage area ~~variationreduction~~. Statistical ~~evidence demonstratesanalyses show~~ that geomorphons-defined landforms correlate with desaturation indicators, enabling the prediction of catchment sensitivity to climate change based solely on a topographic ~~analysisattributes~~.

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Short summary. This ~~studyresearch demonstrates-shows~~ that the response of groundwater-dependent wetlands to recharge changes can be ~~accurately-predicted solely based on-from~~ landform properties ~~alone, providing a practical and scalable approach for wetland vulnerability assessment~~. ~~We reveal that m~~Mountain catchments are less sensitive to recharge changes than ~~lowland-flat catchmentsones~~,— due to fewer but more persistent seepage areas. ~~These results It offers critical insights for evaluating thesupport a scalable approach to assessing wetland vulnerability of catchments to climate change, with practical implications -impacts and has direct implications-~~for water resource management and conservation planning ~~in~~ diverse landscapes.

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2.1. Introduction

Changes in precipitation regimes and increasing temperatures driven by climate change are anticipated to significantly affect both surface and subsurface water resources (Berghuijs et al., 2024; Konapala et al., 2020; Taylor et al., 2013). Extended drought periods and reduced recharge are expected to threaten the functioning of groundwater-dependent ecosystems (Kløve

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et al., 2014; Rohde et al., 2024; Tetzlaff et al., 2024). These ecosystems rely on groundwater contributions to maintain their ecological structure and functional integrity, including processes that support biodiversity and key ecosystem services (Barron et al., 2014; Doody et al., 2017; Eamus & Froend, 2006). They encompass both terrestrial and aquatic environments, including wetlands, springs, rivers (riparian, aquatic, and hyporheic zones), lakes, grasslands, forests, as well as coastal and estuarine habitats (Eamus & Froend, 2006; Kløve et al., 2011). The extent to which groundwater-dependent ecosystems are vulnerable to climate-induced reductions in recharge depends not only on the hydrogeological properties of the underlying aquifer, but also on the role of landscape morphology in shaping groundwater flow and discharge patterns (Gleeson & Manning, 2008; Singha & Navarre-Sitchler, 2022). Identifying the physical controls on groundwater emergence at the land surface is therefore essential to improve our ability to anticipate groundwater-dependent ecosystems responses to climate variability.

Groundwater seepage occurs when the water table intersects the topography. Thus, landforms influence both its spatial distribution and temporal dynamics (Bresciani et al., 2014, 2016; Sophocleous, 2002). The interaction between groundwater and topography significantly impacts the resilience of groundwater-dependent wetlands to climate variability (Cuthbert et al., 2019; Scanlon et al., 2023). Considering steady-state groundwater flow systems, the depth of the water table, and ~~so~~ the distribution of flow paths and groundwater seepage areas, are controlled by the groundwater recharge rate (R), the topography and by the hydrodynamic properties of the aquifer through its hydraulic conductivity (K), (Condon & Maxwell, 2015; Rath et al., 2023; Tóth, 1963; Zhang et al., 2022). An equivalence of effects between R and K has been demonstrated (Bresciani et al., 2014; Haitjema & Mitchell-Bruker, 2005; Jamieson & Freeze, 1982), allowing a convenient focus on the dimensionless $\frac{K}{R}$ ratio and the topography. In non-anthropized contexts, ~~the~~ the groundwater table is typically near the surface in low-relief and/or humid regions, and deeper in rugged terrain and/or arid regions. However, the hydrogeological response and seepage dynamics to varying landscapes and topographic features are not straightforward and difficult to predict.

Analytical solutions have been proposed to quantify the extent of groundwater seepage under varying $\frac{K}{R}$ at the hillslope scale, using simplified groundwater flow equations (Bresciani et al., 2014, 2016). Marçais et al. (2017) conducted modeling experiments to estimate seepage extent and dynamics using a 2D representation of the equivalent hillslope. While these approaches are applicable in shallow aquifers, where flow predominantly follows the topography, they do not capture the complexity of 3D groundwater flow, especially under low water tables or steep reliefs. A few 3D numerical modeling experiments have been undertaken, mainly for sensitivity studies with conceptual surface and subsurface geometries (Carlier et al., 2019; Gauvain et al., 2021; Gleeson & Manning, 2008; Welch et al., 2012). There is a pressing need to better understand ~~seepage-the~~ the distribution and dynamics of groundwater seepage, particularly in light of the complex considering the intricate topographic characteristics nuances of real-world conditions-landscapes and the 3D nature of groundwater flow. This-Such knowledge is ~~essential-critical for to~~ essential-critical for predicting the extent of ~~groundwater-seepage~~ groundwater seepage and ~~the persistence of groundwater-its~~ the persistence of groundwater dependent wetlands under future climate scenarios.

To address this knowledge gap, we designed a numerical experiment to ~~Our study aims to~~ model the partitioning of- 3D groundwater flows and ~~the their-seepage~~ the seepage extent of seepage across different landscapes, from ~~lowland-flat~~ lowland to high mountain

settings, considering various $\frac{K}{R}$ values. We applied this experiment on 60 catchments located in northern Chile, selected for their rich diversity of geomorphological contexts. Additionally, we aim to identify appropriate topographic indicators that explain the variety of hydrogeological responses and provide statistical means to extrapolate our findings to ungauged or data-scarce regions. By linking geomorphologic key topographic patterns characteristics of the catchments to groundwater seepage dynamics predicted by the model, we seek to improve the prediction of wetland desaturation risks sensitivity under changing climate conditions. This approach supports the development of transferable frameworks for assessing the vulnerability of groundwater-dependent ecosystems – vulnerability across heterogeneous terrain and provide statistical means to regionalize our findings. behaviors, providing statistical means to extrapolate our results to other contexts. We developed a parsimonious 3D groundwater flow modeling approach, which we applied to sixty 60 catchments along 1,800 km of the northern Chile. This choice was motivated by the rich diversity of geomorphological contexts, allowing the exploration of a wide range of hydrogeological responses.

3.2. Material and Methods

3.2.1. Geomorphological context

The study area is located in northern Chile between Santiago and the Peruvian border (~1,800 km long). The landforms diversity results from the specific tectonic and weathering processes involved in the Andes. This process resulted in the formation of a longitudinal valley called the Central Depression, which is bounded by two cordilleras, the Coastal Cordillera and the Principal Cordillera, both composed mainly of volcanic-sedimentary rocks (Hartley & Evenstar, 2010; Jordan et al., 1983). The Coastal Cordillera forms an intermediate mountain range with an average elevation between 1,000 and 2,000 m.a.s.l., while the Principal Andean Cordillera has maximum elevations close to 7,000 m.a.s.l. (Figure 1a) (Armijo et al., 2015; Charrier et al., 2007). The Central Depression delineates a sedimentary basin rich in Quaternary alluvial deposits with variable thicknesses, ranging from about 250 m near Santiago (Yáñez et al., 2015) to almost 1,000 m in the northern regions of Chile (Hartley & Evenstar, 2010; Jordan et al., 2014; Nester & Jordan, 2011). Specifically, the Pre-Cordillera is a transition zone between the Central Depression and the Western Cordillera, with catchment characteristics that vary from nearly flat terrain to mountainous regions with steep slope gradients and typical mountain front geomorphology (Figure 1a). The diversity of these environments provides an excellent opportunity to explore a wide range of topographic settings, including flat catchments, mountain-front areas, incised mountain catchments, volcanoes, and high mountain peaks.

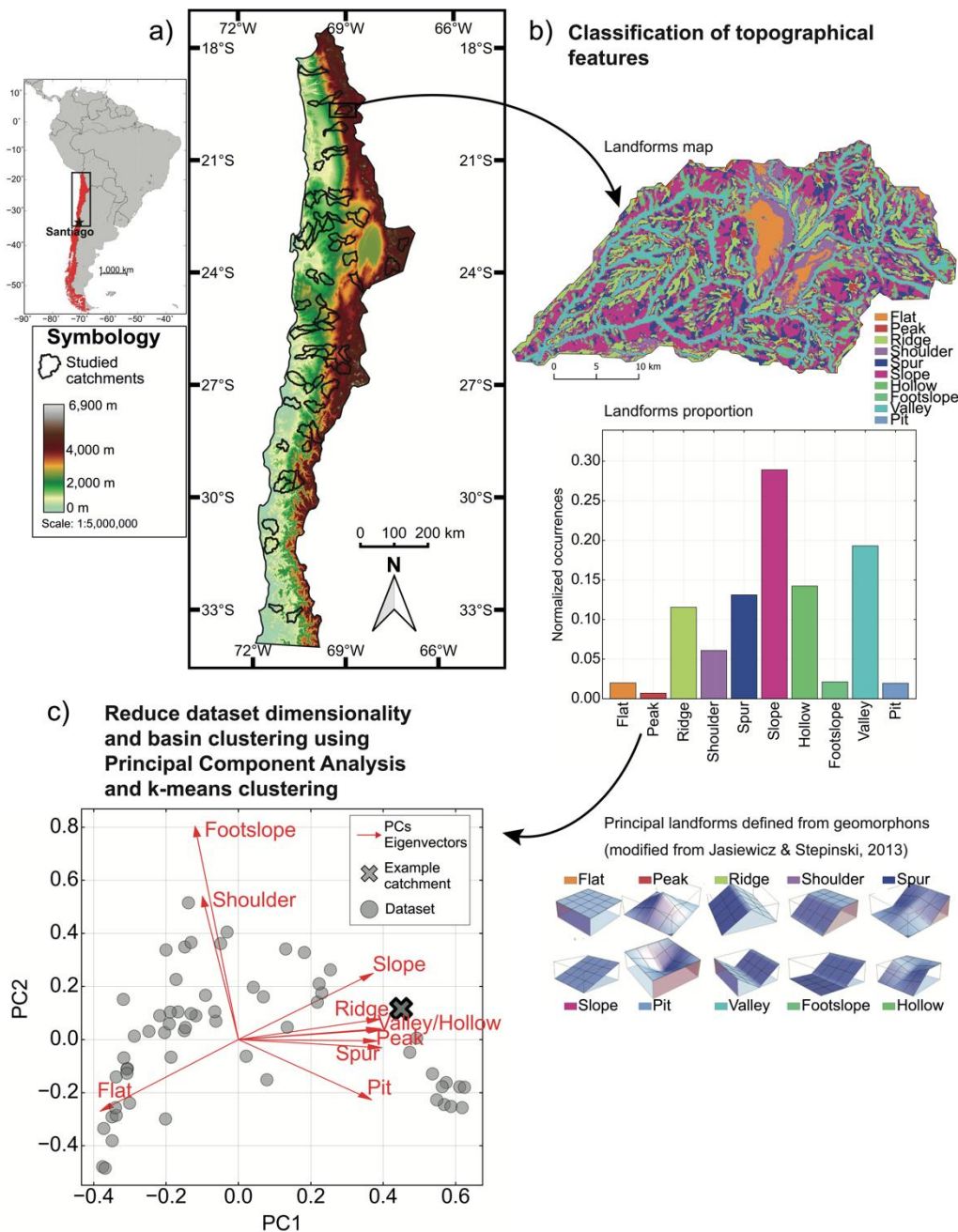


Figure 1: Methodological workflow for topographical classification and analysis. (a) Location and topographic map of the study area in northern Chile, with the boundaries of the 60 studied catchments highlighted in black. **(b)** Example of landform classification within a single catchment, including a landform map, the proportion of landform types, and an illustration of the principal landform categories defined by geomorphons (adapted from Jasiewicz & Stepinski, 2013). **(c)** Catchment categorization using Principal Component Analysis (PCA) for dimensionality reduction and clustering. The selected-example catchment is plotted in the PCA space, illustrating its position relative to the first two principal components (PC1 and PC2) and to the whole dataset (grey dots). Red arrows represent the eigenvectors associated with different landform types, showing their contribution to the PCA axes.

3.2.2.2. Classification of catchment topographies

100 We considered the catchment boundaries of the global catchment database HydroATLAS (Lehner & Grill, 2013). We chose to limit the size of the catchments to between 500 and 1,500 km² by considering level 8 of HydroATLAS. To cover different geomorphological and tectonic settings, we selected ~~sixty~~60 catchments within our study area (indicated by ~~colored-black~~ boundaries in ~~Figure 1~~Figure 1a). We extracted the topography from the ~~SRTM (Shuttle Radar Topography Mission, 90 m resolution)~~ digital elevation model (DEM) ~~from the SRTM (Shuttle Radar Topography Mission, 90 m resolution)~~.

105 We used the geomorphons classification method proposed by Jasiewicz & Stepinski (2013) to categorize the ~~topographies~~ *landform features within each catchments; e.g., flat, peak, ridge, shoulder, spur, slope, pit, valley, footslope, and hollow.* ~~into ten different landforms (Figure 1~~Figure 1b, note that). ~~G~~geomorphons-defined landforms are italicized throughout the text for improved readability). This methodology is based on elevation differences in eight directions relative to the reference cell. This operation is reproduced for each cell of the DEM, identifying a shape for each of these cells (~~Figure 1~~Figure 1b). Unlike

110 the direct cell neighbor method (e.g., slope, curvature, or roughness), the geomorphons method allows ~~to capture~~for capturing landforms at larger scales by defining a search radius around the reference cell, the look-up distance in Jasiewicz & Stepinski (2013). Here we defined ~~the search radius~~it as a function of the ~~equal to the~~ hillslope characteristic length:

$$L = \frac{1}{2D} \rightarrow L = \frac{1}{2 \cdot \frac{l}{A}}, \quad \text{Equation (1)}$$

where L is the catchment feature length, l is the river network length, D is the drainage density, and A is the catchment area. The river network is defined using a surface flow accumulation routine available in the Whitebox tool Python package

115 (Lindsay, 2016). Combining principal component analysis (PCA) and k-means clustering ~~methods~~ (Figure 1Figure 1c), we categorized the catchments by their dominant ~~topographical-landform~~ features ~~based on landform proportions (Figure 1~~Figure 1b). PCA is a classical statistical method used to reduce the dataset dimensionality by transforming the original variables into a new set of uncorrelated variables, called principal components (PC), which capture the maximum variance in the data. The k-means clustering approach allows us to identify groups of catchments belonging to the cluster with the nearest mean within

120 the new PC space (~~Figure 1~~Figure 1b and c). ~~Here, we defined 3 main categories~~clusters of catchments typical of flat, ~~intermediate~~transitional, and mountain settings. Python code and trained models are available on ~~the~~ repository-(Marti et al., 2025)(Marti et al., 2024).

3.3.2.3. Numerical modelling of groundwater seepage area extent

A three-dimensional numerical groundwater flow model was developed for each catchment. The models were constructed and

125 run using the MODFLOW-2005 software suite (Harbaugh, 2005) with the NWT solver (Niswonger et al., 2011), and managed through the Python-based interface FLOPY (Bakker et al., 2016). The diffusivity equation was solved under steady-state conditions for unconfined flow.

The horizontal discretization followed the DEM resolution, set at 90 meters (Figure 2a), while the vertical discretization consisted of ten layers with exponentially increasing thickness (Figure 2b). To limit boundary effects, a buffer zone extending the model domain by 20% around each catchment was added, expanding the modeled domain area by 20%, ensuring boundary conditions did not impact the seepage distribution. A sensitivity analysis (Abhervé et al., 2023) of the extent of the buffer zone was performed to ensure that conditions did not impact the seepage distribution. A drain boundary condition (with a conductance equal to the product of hydraulic conductivity with horizontal cell area $K \cdot dx \cdot dy$ divided by the cell mid-thickness) was set on the topography using the eponymous packages in MODFLOW to allow exfiltration of groundwater wherever the water table rises to intersect the land surface. This method ensures that discharge occurs naturally along the topography, mimicking surface-connected wetlands and springs without imposing fixed fluxes or predefined discharge zones. To solely focus on the effects of topography in the redistribution of groundwater seepage, we imposed homogeneous and isotropic hydraulic conductivity (K) across all modelled catchments. This simplification ensures that variability in seepage behavior arises solely from differences in landscape geometry and water table positions, rather than site-specific geological heterogeneity. Hydraulic conductivity (K) was set to be homogeneous and isotropic.

Various water table positions relative to the topography were derived by setting different values of the $\frac{K}{R}$ ratio, ranging from 100 for fully saturated conditions to 10,000 when all simulated catchments reached near full desaturation (i.e., when the normalized seepage area $S_A^* = \frac{\text{seepage area}}{\text{catchment area}} (S_A^*) < 1\%$ reaches 1%). $\frac{K}{R}$ values were logarithmically spaced within this interval, and simulations were stopped if the catchment's seepage area fell below the 1% threshold (Figure 2c). This allows us to consider a full range of conditions from humid to arid climates and low- to high-hydraulic conductivity settings. This modeling workflow resulted in a total of 1,793 simulations.

For each catchment, we perform a power law fit on the relationship between seepage area extent and $\frac{K}{R}$ further mentioned as the desaturation function (Equation 2a, and red curve in Figure 2c). This allows us to capitalize on the observed linear relation between $\log(S_A^*)$ and $\log(\frac{K}{R})$:

$$S_A^* = \left(1 + \left(\frac{K}{R} \right)^2 \right)^n \quad \text{Equation (2a)}$$

$$\frac{dS_A^*}{d \frac{K}{R}} = \frac{2n K}{\lambda^2 R} \frac{S_A^*}{1 + \left(\frac{K}{R} \right)^2} \quad \text{Equation (2b)}$$

$$\frac{dS_A^*}{d \frac{K}{R}} \approx \frac{2n S_A^*}{\frac{K}{R}} \text{ when } \frac{K}{R} \gg \lambda \quad \text{Equation (2c)}$$

The desaturation function is determined by the proportionality constant, λ , which can be associated with a desaturation threshold, i.e., the critical value of $\frac{K}{R}$ above which the catchment begins to desaturate. The negative desaturation exponent, n , directly affects the rate of change in seepage extent as $\frac{K}{R}$ increases, as shown in Equations 2b and 2c. It can be viewed as a measure of the sensitivity of the seepage area extent to a deepening of the water table: for a given pair of seepage area and $\frac{K}{R}$, a lower n indicates a higher sensitivity of the catchment to a decrease of the water level. We estimated n considering seepage area extents lower than 20% of the catchment area, which are more representative of real-world conditions, i.e., by giving more weight in the fit to the higher $\frac{K}{R}$ ratios.

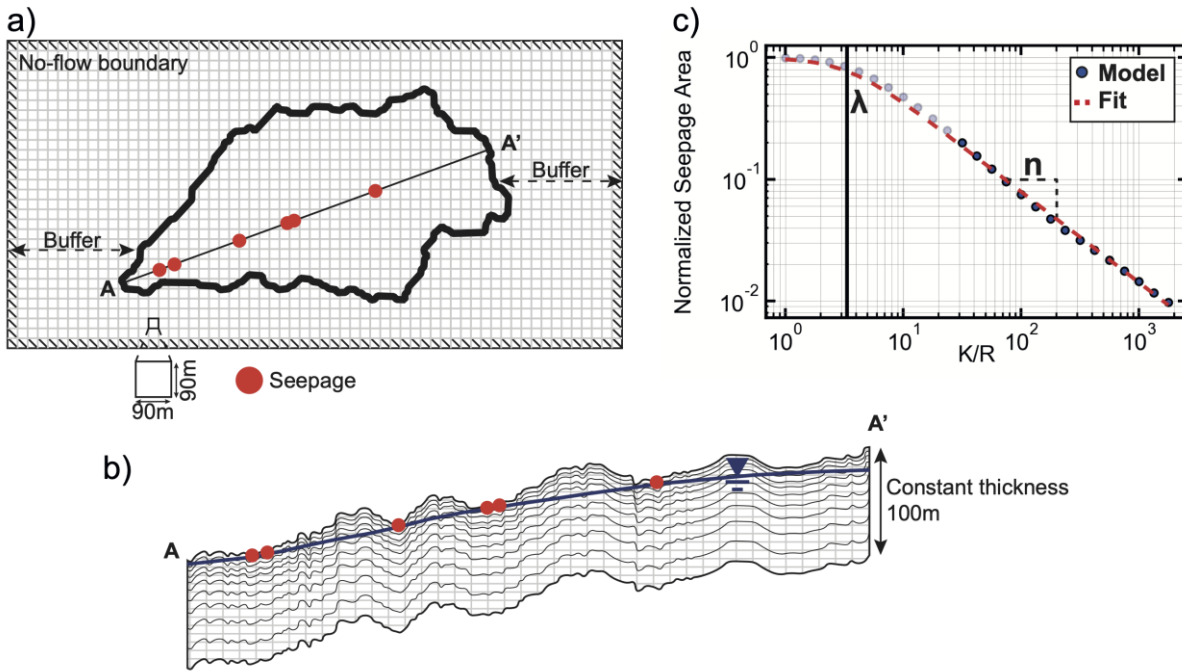


Figure 2: Model settings for one example catchment: (a) Horizontal discretization and buffer zone beyond catchment limits, (b) AA' cross-section including vertical discretization and an arbitrary water table intercepting the topography creating seepage areas (red dots), (c) Example of results of normalized seepage area with respect to K/R (grey and blue dots) with the power law fit for Eq. 2a (dashed red curve). The blue dots represent the normalized seepage area < 20% where the fit is weighted is enhanced. [TO BE COMPLETED]

2.4. Regionalization with ~~Random forest~~ Random Forest method algorithm

To predict the desaturation response metrics λ and n from topographic descriptors and regionalize our findings, we employed Random Forest regression using the scikit-learn library in Python (Pedregosa et al., 2011). The input features for the model were the first two principal components (PC1 and PC2) derived from the ~~sixty~~ 60 catchments. Random Forest models were trained independently for λ and n . Model performance and robustness were assessed using a bootstrap resampling procedure with 5,000 iterations. In each iteration, 10 catchments were randomly selected as a test set, while the remaining 50 were used for training. The coefficient of determination (R^2) was calculated on the test data for each iteration, and the resulting R^2 distribution was used to evaluate model reliability (see Supplementary Material S2 for Kernel Density Estimate of R^2 values). Hyperparameter tuning for each model was performed using GridSearchCV with 2-fold cross-validation within each training subset. The tested parameter grid included $n_estimators \in \{50, 200, 500, 1000\}$ and $max_depth \in \{None, 2, 10, 20\}$. The best combination of hyperparameters was used to retrain the model on the full training set in each iteration. The final Random Forest model was defined as the one achieving the best trade-off in predictive accuracy for both λ and n , and it was applied to

predict desaturation metrics in ~~sixty630~~ ^{three} additional catchments located in South Chile. ~~{@Etienne, please add detail on the methodology you use and move the supplementary material dedicated to this to the results as suggested by the reviewer}~~

We finally employed a Random Forest regression on the dataset to predict λ and n based on topographic parameters (PC1 and PC2) for sixty three catchments located both in the same study area and expanding further South inside Chile (Figure 4d and e). We defined PC1, PC2 and clusters for these new catchments using the originally trained PCA and k means model (Figure 4c). Regarding training and testing of the Random Forest algorithm, we used the original sixty catchments dataset. This initial analysis involved 5,000 iterations of sampling with replacement, each using 10 test catchments, with the remaining 50 catchments used for training. This resampling approach was adopted to assess the robustness of the estimations in the presence of random variations within the selected test and training data and was evaluated calculating the coefficient of determination (R^2) within the tested data (see Supplementary Material S2 for Kernel Density Estimate (KDE) plot of R^2 distribution). We defined the model used for predictions based on the best compromise to estimate both λ and n . Hyperparameters (number of trees and maximum depth) were tuned using cross validation techniques.

4.3. Results

4.1.3.1. Typology of catchments topography

We evaluate the proportion of main geomorphons on the ~~sixty60~~ catchment dataset. The PCA analysis (Figure 1Figure 1Figure 4c) resulted in a first component (PC1) explaining 75.4% of the total variance, and the first two components (PC1 and PC2) combined explaining 86.8% of the total variance. This result indicates a strong relation between the landforms description from geomorphons analysis in the catchments and the reduction into 2 dimensions. We found that PC1 mostly represents the differentiation between *flat* and *slope* landforms, with eigenvector magnitudes of -0.4 for the *flat* landform and 0.4 for the *slope* landform. *Slope* landform is associated with the *peak*, *ridge*, *valley*, *hollow*, *spur*, and *pit* forms, all showing similar eigenvectors magnitude on PC1. Regarding PC2, the *footslope* and *shoulder* forms are the main control with an eigenvector magnitude of respectively, 0.8 and 0.5. *Flat* and *slope* forms show eigenvectors magnitudes of -0.2 and 0.2 along the PC2 axis. To further support and illustrate this description, the catchments are grouped into three clusters, ~~as a resultsresult of the k-means clustering, (colored dots indisplayed with different colors in the subsequent Figures 3 and 4-Figure 1e and colored catchments contour on Figure 1a).~~ The red cluster is ~~highly influenced by the~~ characterized by relatively **flat** landforms ~~as lowland catchments would~~. Conversely, the blue cluster is strongly influenced by *slope* and associated landforms along PC1 (*ridge*, *valley*, *peak*) representative of **mountain** catchments with incised valleys, and narrow valley bottoms. The green cluster exhibits more dispersion in the represented catchments. This cluster acts as a transition between the red and blue clusters. It contains catchments most influenced by *footslope* and *shoulder* forms. Positioned centrally between the two extreme clusters,

this cluster serves as a transition zone between flatter areas and mountain catchments, possibly including catchments showing both flat and mountainous characteristics, as observed at mountain fronts.

215 To facilitate comprehension and illustration, the ~~catchment categories~~~~clusters~~ ~~se~~ ~~clusters~~ are referred to as ~~lowland-flat~~ ~~catchment~~ ~~cluster~~ for the red cluster, ~~mountain~~ ~~cluster~~ ~~catchment~~ for the blue cluster, and ~~transitional~~ ~~cluster~~ ~~catchment~~ for the green cluster thereafter.

4.2.3.2. Seepage distribution evolution with increasing $\frac{K}{R}$

220 ~~Figure 3~~~~Figure 3~~~~Figure 3a~~ illustrates the evolution of seepage area, normalized by catchment area, as a function of $\frac{K}{R}$ for all ~~sixty~~~~60~~ catchments. Four specific catchments are highlighted with sharper lines for further discussion. As expected, lower $\frac{K}{R}$ values result in fully saturated catchments, while as $\frac{K}{R}$ increases, all catchments progressively desaturate at varying rates. For instance, at a normalized seepage area of 20%, the corresponding $\frac{K}{R}$ values range from 20 to 250.

225 ~~Similar to the distinct landform clusters,~~ ~~t~~ The desaturation behavior ~~can be clearly differentiated~~ ~~differentiated for the~~ ~~of these~~ ~~3 clusters~~ ~~categories~~ ~~clusters~~ of catchments (Figure 3a) ~~is clearly defined (Figure 1),~~ confirming that variations in seepage distribution are predominantly driven by topographical effects. The power law fit of seepage distribution (Equation 3a) for each of the ~~sixty~~~~60~~ catchments results in λ values ranging from 2.05 to 37.03 and ~~n~~ values ranging from -0.44 to -0.31. The fit shows minimal RMSE values between 0.01 and 0.08, indicating that seepage evolution with increasing $\frac{K}{R}$ can be successfully parameterized with only two parameters, λ and n .

230 Regarding the desaturation threshold, λ , the mountain ~~cluster~~ ~~catchments~~ shows lower values than the ~~lowland-flat ones~~ ~~cluster~~. The transitional ~~catchments~~ ~~cluster~~ ~~demonstrates~~ ~~show~~ intermediate behavior, reaching higher λ values than the mountain ~~cluster~~ ~~catchments~~ but lower than the ~~lowland~~ ~~cluster~~ ~~flat ones~~. Regarding the desaturation exponent, n , within the low-saturation domain ($\leq 20\%$), the mountain ~~cluster~~ ~~catchments~~ exhibits slower desaturation rates, while the ~~lowland~~ ~~cluster~~ ~~flats~~ presents faster desaturation rates. The variability in desaturation slopes for the transitional ~~catchments~~ ~~cluster~~ is more pronounced, reflecting a mix of behaviors within this zone, yet it again shows intermediate behavior relative to the other two clusters.

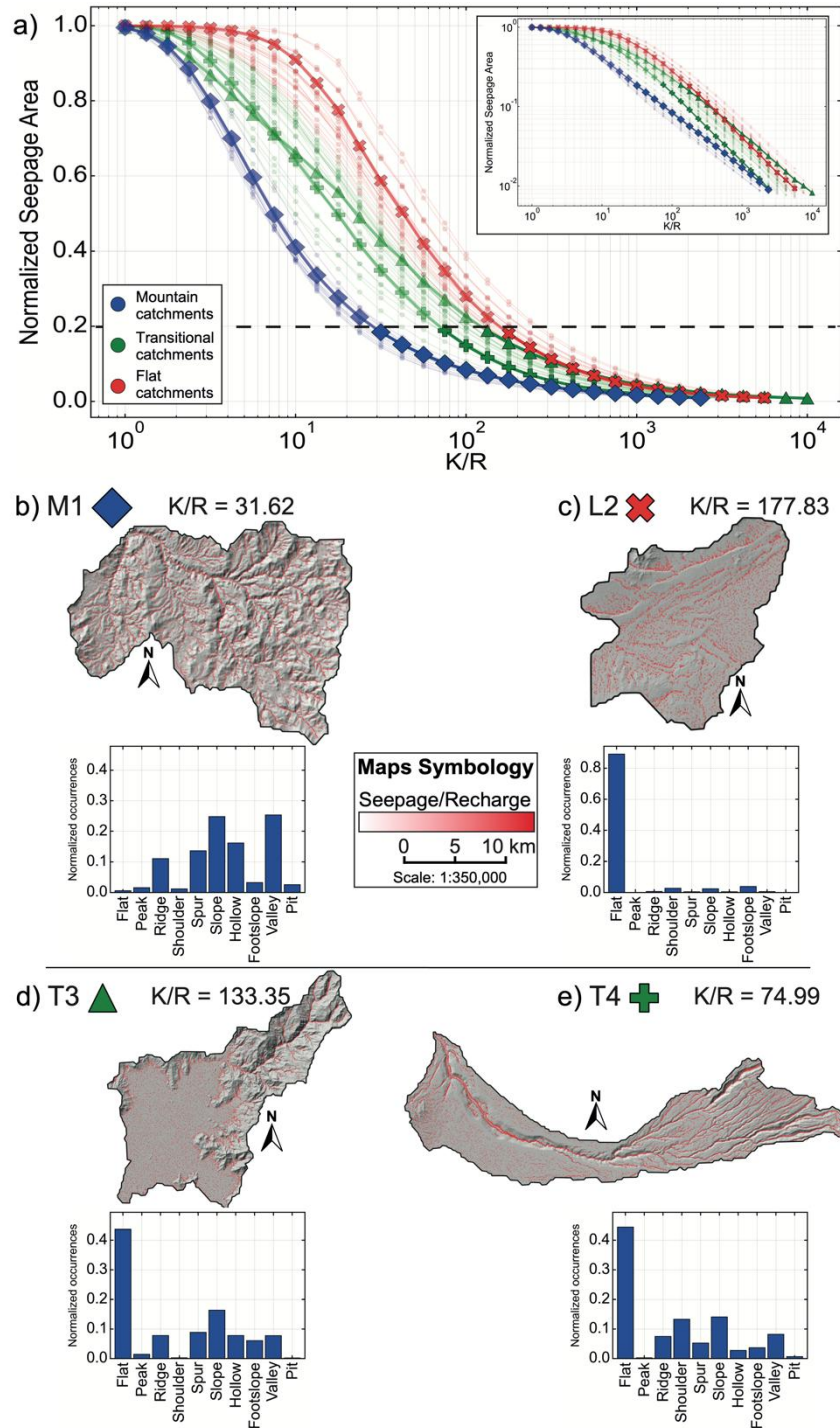


Figure 3: (a) Normalized seepage area against K/R for the sixty catchments (colored lines with markers), including log-log plot on the upper-right corner. Four illustrative catchments are highlighted: mountain type M1 (blue diamond, (b)), lowland-flat type FL-2 (red cross, (c)), transitory-transitional type T3 (green triangle, (d)) and T4 (green cross, (e)). Details include the topographic map

240 overlaid by the seepage ~~area extent~~ at an arbitrary value of 20% (red mask) with corresponding $\frac{K}{R}$ value ~~followed along with by the~~
landforms ~~histogram distribution statistics~~.

4.3.3.3. ~~Groundwater s~~Seepage patterns ~~extent~~ in ~~four~~ representative catchments

245 ~~Figure 3~~Figure 3 highlights four distinct catchments: M1, representative of the mountain ~~cluster catchments~~; ~~FL2~~, representing
the ~~lowland-flat cluster catchments~~; and T3 and T4, showing the range of responses within the ~~transitory-transitional~~
~~catchments cluster~~. We present the seepage ~~over recharge~~ distribution over ~~laid on~~ the topographic map and the landform
proportions for each catchment (~~Figure 3~~Figure 3b, c, d, and e).

For M1 (~~Figure 3~~Figure 3b), characterized by low λ and high n values, it exhibits the typical seepage distribution of
mountainous regions. At a normalized area of 0.2, seepage primarily congregates in topographic lows, such as river valleys,
while ridges and peaks desaturate due to their significant elevation compared to the surrounding terrain. Conversely, ~~FL2~~
250 (~~Figure 3~~Figure 3c), with high λ and low n values, suggests that the water table remains closer to the surface in ~~lowland-flat~~
settings.

For T3 and T4, their landform proportions (~~Figure 3~~Figure 3d and e) reveal similar values for most forms, except for a higher
proportion of *shoulder* and *footslope* forms in T4. This increased prevalence of *shoulder* landform in T4 is due to a prominent
incised river valley in the eastern part of the catchment.

255 Examining T3's seepage distribution, it initially aligns with the mountain ~~cluster catchments~~ with a low desaturation threshold
(λ). Then, in the range of $1 < \frac{K}{R} < 10$, a substantial change in ~~the desaturation function slope~~ is observed, with the distribution
~~intersecting pattern converging toward the ones typical of that of the lowland cluster flat catchments~~ for high $\frac{K}{R}$ values,
ultimately being the last catchment to reach a saturation level of $< 1\%$. This behavior can be explained by looking at the spatial
distribution of seepage for T3 (~~Figure 3~~Figure 3d). A clear ~~demarcation contrast~~ exists between the flat western area and the
260 mountainous settings to the east. At higher elevations, desaturation occurs at lower $\frac{K}{R}$ values ~~dominated by the steep landforms~~
~~of the mountain settings and~~, resulting in a low desaturation threshold (λ). Subsequently, at a normalized area of 0.2, the
catchment ~~behaves like the lowland cluster~~ ~~desaturation is mostly controlled by the western flat terrains, influenced by the~~
~~western part of the catchment~~.

Conversely, T4's seepage distribution exhibits an opposite pattern. It initially mirrors the ~~lowland-flat~~ cluster with a higher λ
265 value, ultimately resembling the mountain cluster characteristics, reaching saturation levels under 1% for similar $\frac{K}{R}$ values. The
seepage spatial distribution for T4 (~~Figure 3~~Figure 3e) shows that ~~flat landforms at~~ higher elevation zones in the western part
of the catchment ~~have already undergone control the initiation of the~~ desaturation ~~and before being mostly controlled tend to~~
~~develop exclusively within by the steep incised valley at lower elevations that tends to sustain the seepage extent. topographic~~
~~lows, specifically at the bottom of the singular river channel.~~

We computed the correlation matrix between the principal components (PC1 and PC2) and the desaturation parameters (λ and n) to assess the strength of the topographical control on desaturation behavior. [Figure 4](#)~~Figure 4~~a shows a strong anti-correlation between λ and PC1, with a Spearman coefficient of $r = -0.96$ ($p < 0.0001$). [Figure 4](#)~~Figure 4~~b displays a strong linear correlation between n and PC1, with $r = 0.76$ ($p < 0.0001$). No other significant correlations were identified (the entire correlation matrix is available in Supplementary Material S1).

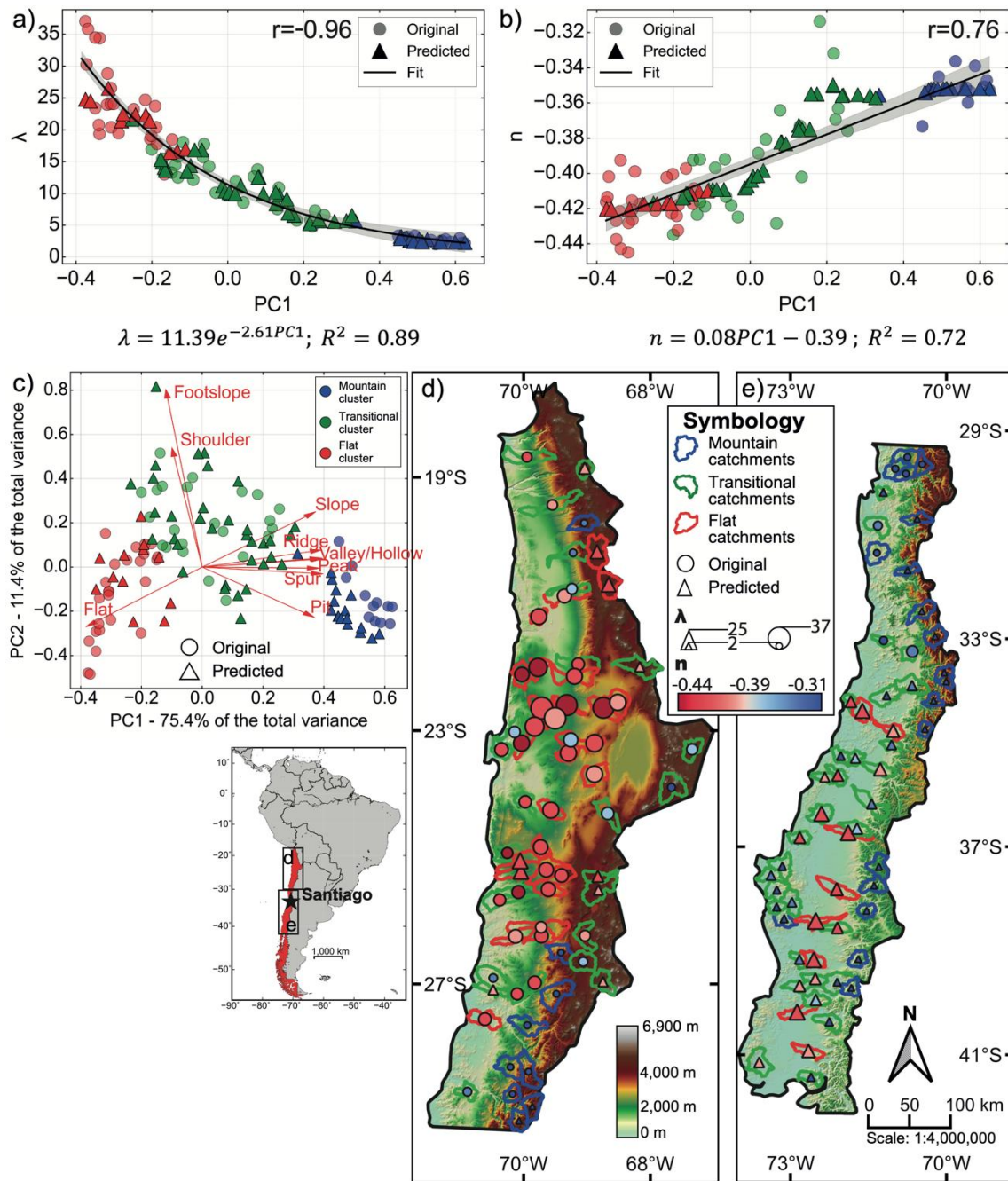


Figure 4: Scatter plots for the original ~~sixty~~60-catchment dataset (dots) with Spearman coefficient r , the equation and the coefficient of determination (R^2) of a global fit (black line with 95% confidence interval) for (a) λ against PC1 and for (b) n against PC1. Random Forest predictions for both parameters are overlaid on the original data (~~crosses~~triangles). (c) PCA plot, for the original (dots) and the prediction (~~crosses~~triangles) datasets. The percentage of variance in the original dataset explained by each component is ~~displayed~~displayed on axis title. (d) and (e) Situation and topographic maps of the study area highlighting the ~~one-hundred-and-twenty-three~~123 catchments with a colored according to the defined ~~catchment clusters~~categoriesclusters (flat, transitional and

mountain). Each catchment is overlaid by a dot (original dataset) or a triangle (prediction dataset) which whose size depends on λ and the color for n .

The catchment categories/clusters are well distinguishable in Figure 4a and 4b. In Figure 4a, the inverse relationship between λ and PC1 is robustly quantified by fitting an exponential function ($R^2 = 0.89$), facilitating a quantitative correlation between λ and PC1, as illustrated in Figure 4a. The mountain cluster is isolated with a low average and variance in λ values. The transitional cluster forms the elbow part of the exponential decay, while the lowland-flat cluster is clearly identified with higher λ values. The variations in λ values are higher in the lowland-flat and transitional clusters/catchments compared to the mountain cluster/ones.

Figure 4b reveals a linear relationship between n and PC1. The excellent-good linear fit ($R^2 = 0.72$) allows for a straightforward quantification of the relationship between PC1 and the negative scaling exponent n and, consequently, the appraisal of the desaturation rate based on landforms ((Equations (2) and (3)). The clusters/catchment categories/clusters are well identified, with the lowland-flat cluster showing lower n values than the mountain cluster.

We finally employed a Random Forest regression on the dataset to predict λ and n based on topographic parameters (PC1 and PC2) for sixty-three catchments located both in the same study area and expanding further South inside Chile (Figure 4d and 4e). We defined PC1, PC2, and clusters for these new catchments using the originally trained PCA and k-means models (Figure 4c). We finally employed a Random Forest regression on the dataset to predict λ and n based on topographic parameters (PC1 and PC2) for sixty-three catchments located both in the same study area and expanding further South inside Chile (Figure 4d and e). We defined PC1, PC2 and clusters for these new catchments using the originally trained PCA and k-means model (Figure 4c). Regarding training and testing of the Random Forest algorithm, we used the original sixty catchments dataset. This initial analysis involved 5,000 iterations of sampling with replacement, each using 10 test catchments, with the remaining 50 catchments used for training. This resampling approach was adopted to assess the robustness of the estimations in the presence of random variations within the selected test and training data and was evaluated calculating the coefficient of determination (R^2) within the tested data (see Supplementary Material S2 for Kernel Density Estimate (KDE) plot of R^2 distribution). We defined the model used for predictions based on the best compromise to estimate both λ and n . Hyperparameters (number of trees and maximum depth) were tuned using cross-validation techniques. Predictions made for λ (Figure 4a) show good consistency with the original dataset both in terms of identifying clusters behaviors and in trend, following the originally defined exponential relation. Regarding n (Figure 4b), we observe a similar accuracy to represent clusters, while the general linear trend is less obvious. We observe for n , while following an increasing trend, diversified response between the clusters with the transitional cluster/catchments exhibiting a greater rate of change in n for an equivalent increment in PC1. Yet, it is a better fit to original data. The spatial distribution of the predicted catchments observed on Figure 4d and 4e, is a good match with the original data, both in terms of topographic characteristics and desaturation function parameters.

Groundwater flow and storage regulate the resilience of wetlands to climate ~~variations~~~~changes~~~~variability~~ (Fan et al., 2019). Variations in topography and landforms across catchments lead to differences in wetland sensitivity to changing recharge by shaping distinct groundwater flow structures. In this study, we provide a quantitative assessment of the controls of landforms on the sensitivity of groundwater-dependent wetlands to aquifer desaturation (~~expressed~~ through variations in ~~the~~ $\frac{K}{R}$ ~~ratio~~) across ~~a total of sixty-one hundred and twenty-three~~123- catchments ~~along in Northern~~ Chile, ~~covering~~ ~~spanning~~ settings from ~~lowlands-flat~~ to ~~high~~ mountains ~~topographies~~. These feedback mechanisms were analyzed using a novel combination of three-dimensional process-based groundwater modeling, geomorphons-based landforms ~~characterization~~~~classification~~, and multivariate statistical analysis, ~~and Random Forest predictions~~ at the regional scale.:-

~~Moreover, the proposed methodology demonstrated strong robustness to outliers and atypical landscape configurations. For example, the Andes Mountains in northern Chile include~~encompass the “Altiplano” region, ~~— characterized by which features extensive flat are~~terrains within an otherwise mountainous setting. The method successfully identified such catchments and classified them as *flat* (Figure 4~~Figure 4d~~ between 19 and 23°S), illustrating its ability to reliably capture dominant landform characteristics ~~capacity to perform reliably across diverse geomorphological contexts.~~

Our results demonstrate that the desaturation functions of catchments can be explained by the typologies in topography~~yes~~ derived from landform categorization. Building on previous works that focused on two-dimensional aquifer geometry, as first introduced by Haitjema and Mitchell-Brucker (2005) and further explored by Bresciani et al. (2014), we show that mountainous regions exhibit lower seepage extents, restricted to incised valleys, compared to ~~lowland-flat~~ catchments at equivalent $\frac{K}{R}$ ratios. However, we demonstrate that mountainous regions are less sensitive to changes in saturation, exhibiting slower desaturation rates.

To disentangle the respective impacts of different landforms, we compared our results with those obtained from the analytical solution proposed by Bresciani et al. (2014) for a 1D hillslope, where one can easily assess the impacts of slope angle and the concavity/convexity of the hillslope (results in Supplementary Material S3). In agreement with our results, the steepness of the hillslope is the primary influence on seepage extent and its variation through changes in groundwater level. Steep slopes begin to desaturate at lower $\frac{K}{R}$ values than gentler slopes. Additionally, for a given change in groundwater level, the rate of change in seepage extent is inversely correlated with slope angle. This aligns with the differences in the desaturation exponent, n , and the desaturation threshold, λ , obtained for the mountain and ~~lowland-flat~~ clusters. Mountain clusters have higher n and λ values, suggesting higher resilience to changes in $\frac{K}{R}$.

Furthermore, the analysis of the simple analytical solution demonstrates that hillslope shape (concave vs. convex) also affects the desaturation function, though to a lesser extent than slope. Concave slopes appear to have a lower λ but a higher n than convex slopes. Similarities between concave and convex hillslopes can be found in the *shoulder* vs. *footslope* in our landform

classification. *Shoulder* and *footslope* is differentiated primarily along PC2, explaining a smaller proportion of the variance in the dataset analyzed here. However, no clear correlation between PC2, n , and λ was found, suggesting a minimal impact of *shoulder* and *footslope* landforms compared to the other ones.

While the aim of the present work is to establish a comprehensive exploration of landform controls on seepage dynamics, several simplifications limit its direct application to specific real-catchment systems. Although the models are based on real topographies from the Chilean Andes, the experiment does not intend to capture actual complexity of hydrogeological systems, but rather to explore a wide enough range of natural landform geometries for comparative analysis. First, we assumed homogeneous and isotropic aquifer properties with a fixed aquifer thickness, thereby neglecting geological heterogeneities, anisotropy, and variability in the depth of the active groundwater flow system (Frisbee et al., 2017; McIntosh & Ferguson, 2021), and consequently the seepage distribution, that can be involved in real landscape. While our use of the dimensionless $\frac{K}{R}$ ratio offers a robust approach for analyzing desaturation responses, future research could benefit from exploring additional parameters that account for catchment geometry, relief, or flow system depth. Additionally, the model results presented here operate under steady-state conditions and exclude the potential impacts of seasonal recharge variability, vegetation feedbacks, or the role of the unsaturated zone near the land surface. Exploring such processes, especially under transient conditions and with heterogeneous parameters, represents a promising perspective for future research.

6.5. Conclusion

To conclude, our study demonstrates that catchment-scale topographic features, quantified through geomorphon-based landform classification, exert a first-order control on groundwater seepage dynamics under varying recharge conditions. By linking these landforms to a desaturation functions, we show that the sensitivity of groundwater seepage extent to climate variability can be predicted from topography alone. This insight enables the development of a robust and scalable framework for assessing hydroclimatic vulnerability, particularly relevant for data-scarce regions. The ability to regionalize desaturation behavior using simple statistical learning tools, such as Random Forests as presented here, opens up new opportunities for applying this approach to ungauged basins in other regions (Hrachowitz et al., 2013). As such, our findings offer not only a methodological advance, but also enabledemonstrate potential for its application to assess the vulnerability of regional-scale groundwater-dependent wetlands and the ecosystem they support to climate change.

Our results establish a robust statistical framework demonstrating a strong correlation between landforms, categorized by the dominant landforms (PC1), and hydrological parameters that assess the sensitivity of groundwater seepage to desaturation with changing recharge. This framework allows for predictions using straightforward statistical learning techniques. The Random Forest algorithm yields highly promising results for the sixty three catchments estimated. This approach provides valuable

insights into assessing catchment vulnerability to climate change on a regional scale, even for ungauged basins (Hrachowitz et al., 2013).

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Open Research

The HydroATLAS global catchments database is freely available at <https://www.hydrosheds.org/hydroatlas>. The SRTM Digital Elevation model is available on NASA website (<https://www.earthdata.nasa.gov/sensors/srtm>). Python code to reproduce the analysis, the trained models (PCA, k-means and Random Forest), and the data used to generate results and figures in this manuscript is publicly available at Marti et al. (2025)(2024). This includes landforms proportion, PCA, cluster information, λ and n values, and seepage area distribution for each catchment of the original dataset. The predicted dataset is also included (PCA, clusters, λ and n estimations). Catchments ID correspond to the HydroATLAS identification.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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