# Multicriterianalysis *Recarga Hídrica*

**Implementing an adjusted Methodology for Identifying Potential Groundwater Recharge Zones: A Case Study in the Municipalities of Aiquile and Pasorapa, Bolivia**

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# Preface

In Bolivia, groundwater plays a vital role in supporting human consumption and agriculture. However, the absence of regulatory policies governing extraction and protecting recharge areas has led to declining water tables, endangering food security (Helvetas 2014). Local initiatives in the cantons Aiquile and Pasorapa aim to establish regulations, but the lack of reliable hydrogeological data hampers effective implementation.

This case study focuses on municipal policies to safeguard groundwater recharge zones and the necessity for a reliable methodology to identify them in the unique conditions of the basin. Managing watersheds, especially in mountainous regions like Bolivia, is crucial for global ecosystem conservation. Groundwater, often overlooked, faces threats due to population growth, poor resource management, and climate fluctuations. Unregulated agriculture and deforestation worsen water quality and quantity, escalating conflicts over natural resources (Helvetas 2014).

Ensuring water security demands regulations and conservation efforts (Figueredo 2019). A comprehensive water management approach, encompassing all sources, is vital, considering water availability's dependence on natural processes and socio-institutional factors.

Aquifers, especially in arid regions, face threats from excessive extraction. Protecting areas facilitating surface infiltration becomes crucial for aquifer recharge. The lack of delineation for these zones emphasizes the urgency in prioritizing ecosystems for effective water management (Sáenz-López et al. 2015).

This study in Aiquile and Pasorapa, Cochabamba, aims to identify aquifer recharge zones using geospatial datasets and a multicriteria analysis. The methodology integrates various data types, leveraging R-Studio environment packages, to delineate optimal recharge areas.

The resulting raster depicts the region's environmental aspects, supporting local policymaking. The analysis reveals potential recharge zones. The study emphasizes the importance of a balanced approach to water management and the need for precise methodologies to identify critical groundwater recharge zones in sensitive ecosystems.

# 1 Introduction

Groundwater's significance in sustaining human consumption and agriculture across Bolivia underscores its critical role. However, the absence of regulatory policies governing extraction and safeguarding recharge areas has led to plummeting water tables, imperiling food security (Helvetas 2014). While some local initiatives aim to establish regulations, the lack of reliable hydrogeological data obstructs effective implementation.

In this specific case study within the cantons Aiquile and Pasorapa, located in the State of Cochabamba Bolivia, the focus rests on a municipal policy aimed at safeguarding groundwater recharge zones and the dire need for a dependable methodology for their technical identification. This method, tailored to the basin's unique conditions, integrates local vegetation's influence on infiltration and emphasizes rainfall's spatial distribution to assess potential recharge, filling the data gaps.

Watershed management and water source preservation, particularly in mountainous regions like Bolivia, hold immense importance for global ecosystem conservation. Groundwater, often overshadowed by surface water, faces escalating threats due to population growth, poor resource management, and climate fluctuations. Land use changes, including unregulated agricultural expansion and deforestation, further imperil water quality and quantity, exacerbating conflicts over natural resources (Helvetas 2014).

Ensuring water security for both urban and rural areas necessitates regulations and conservation efforts (Figueredo 2019). Recognizing water availability's dependency on both natural processes and socio-institutional factors, a comprehensive approach to water management encompassing all sources is vital.

The focus on aquifers, especially in arid regions, gains paramount importance as unchecked extraction threatens these primary water sources. Protecting areas facilitating surface infiltration, crucial for aquifer recharge, becomes imperative. The lack of delineation for these recharge zones underscores the urgency in prioritizing ecosystems and acknowledging their strategic value for effective water management (Sáenz-López et al. 2015).

Identifying and preserving these zones require consensus-building between authorities and local stakeholders. Participatory methodologies, such as those emphasized by Matus et al. (Matus 2007), that integrate scientific rigor with local knowledge, play a pivotal role in identifying potential aquifer recharge zones within hydrographic sub-basins. These approaches offer a cost-effective means to bridge the data gap and involve community perspectives in preservation efforts.

# 2 Frame of Reference Aiquile and Pasorapa

The Casestudy took place in the State of Cochabamba: Aiquile and Pasorapa, situated in the Cochabamba's Valle Alto region. Renowned for extensive agricultural land, Aiquile and Pasorapa provide various produce. Additionally, water sources in the adjacent mountains serve as crucial irrigation water for other municipalities. Cochabamba's Valle Alto region has grappled with internal and inter-municipal disputes over water rights. Authorities are formulating policies focused on safeguarding recharge zones and water sources.

Despite its geographical significance, emphasis on surface water sources has sidelined direct extraction of groundwater through wells, limiting understanding of hydrogeological processes and aquifer recharge factors. Climatic uncertainties altering precipitation patterns exacerbate water security concerns, leading to prolonged periods of water stress.

Thus, the study aims to devise a methodology for identifying potential aquifer recharge zones, considering Aiquile and Pasorapa's unique biophysical and social characteristics. These findings aim to support the proposed municipal policy in Aiquile and Pasorapa.

Given the absence of a standardized methodology, this approach draws from Oscar Matus' method - a cost-effective, scientific, and participatory approach adaptable to diverse scenarios. By integrating local knowledge with detailed biophysical aspects, the methodology encourages community involvement, influencing decision-making processes regarding territorial and natural resource management. Its potential replication extends regionally and nationally.

# 3 Methodology of the Case Study

This Multicriteria Analysis employs numerous Raster and Vector Layers, integrating weighted factors to delineate optimal areas for natural water recharge zones *(Zonas de Recarga Hídrica)*. The entire project is conducted within the R-Studio Environment. Key packages utilized in achieving the final results are listed here R-Studio Libraries, delivering essential functions for the conducted calculations.

The Following Data has been used. The Code used can be seen in the Appendix.

| Data Name | Data Type | Sources |
| --- | --- | --- |
| Political Map | Vector | gadm.org |
| Geology | Vector | geo.gob.bo |
| Vegetation | Vector | geo.gob.bo |
| Precipitation | Raster | worldclim.org |
| DEM | Raster | Hydrosheds.org |
| Land Use | Raster | GLAD dataset |
| Satellite Data | Raster | glovis.usgs.gov |

The Data Processing in the first step is filtering by the Frame of Reference. Vegetation Data has been filtered to "Cochabamba". The Frames are being intersected by the Frame of Reference - The Aiquile-Shape and the Pasorapa-Shape provided by the political Map from gadm.org. For further Information see the Code in the Appendix.

## 3.1 Satellite Data

### 3.1.1 Vegetation Indices calculation

The Normalized Difference Vegetation Index (NDVI) is a pivotal tool in assessing vegetation health and density using remote sensing data, in this case from satellite imagery. Computed by measuring the contrast between visible and near-infrared light reflected by vegetation, NDVI values range between -1 and 1.

NDVI's application spans various fields. In agriculture, it aids in monitoring crop health and detecting areas requiring attention, such as water stress or disease outbreaks. Ecologists

employ NDVI to analyze changes in ecosystems, tracking deforestation or assessing habitat health. Higher values of the NDVI signify dense, healthy vegetation, while lower values indicate barren land or water bodies. Therefore there is a strong positive correlation between NDVI and biomass according to Khaple et al. (2021).

Detailed Information about the Vegetation-Indices calculation and Color Bands used in the Process can be seen in the Appendix.

### 3.1.2 Reclassification NDVI-Index

The following table has been used to reclass the NDVI-Index into weighted-values between 0 and 1. The Code being used can be seen in the Appendix.

Table 3.2: Reclassification table of the NDVI-Index in Aiquile and Pasorapa

| from | to | becomes | Class |
|------|------|---------|----------|
| -Inf | 0.00 | 0.2 | Very Low |
| 0.00 | 0.05 | 0.4 | Low |
| 0.05 | 0.20 | 0.6 | Moderate |
| 0.20 | Inf | 1.0 | High |
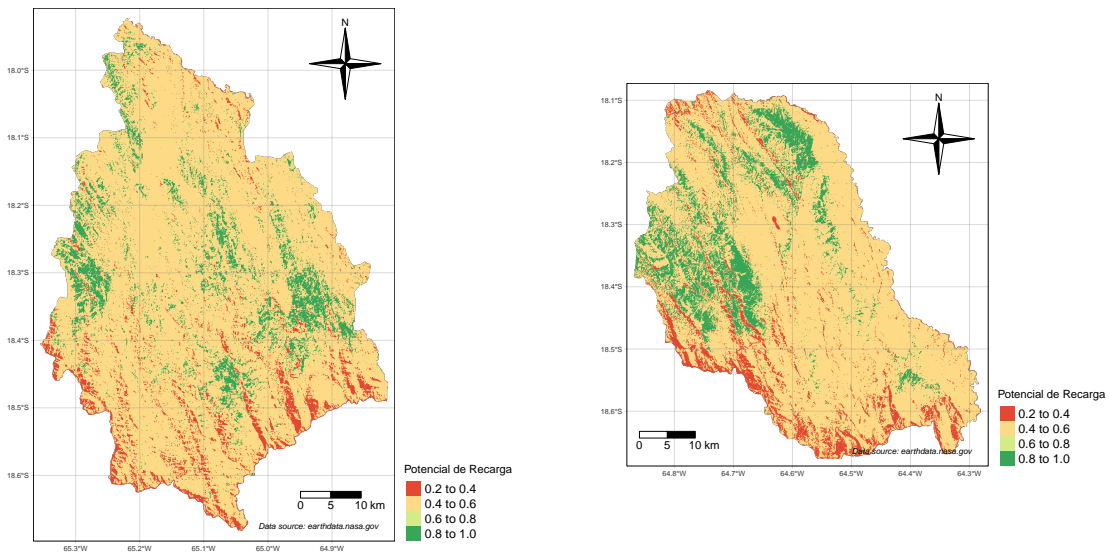


(a) Reclassified NDVI-Index Aiquile

(b) Reclassified NDVI-Index Pasorapa

Figure 3.1: Reclassification Result of the NDVI-Index in Aiquile

## 3.2 Precipitation Data

The following Data by worldclim.org resembles Precipitation Data on a 30 Arc Second Accuracy. The format provides one Raster-Layer for each month. The following Loop has been written in order to facilitate the Casting process.

The following 12 Raster-Layers have been summed to ensure we have one Raster for further classification. The Result is one Raster-Layer that contains the complete Precipitation of the average year from 1970-2000. The Code used can be seen in the Appendix. For the reclassification the same values from Rodriguez-Levy et al. (2023) have been used.

Table 3.3: Reclassification Result of the Precipitation Data

| from | to | becomes |
|------|------|---------|
| 600 | Inf | 1.00 |
| 550 | 600 | 0.75 |
| 500 | 550 | 0.50 |
| 450 | 500 | 0.25 |
| -Inf | 450 | 0.00 |
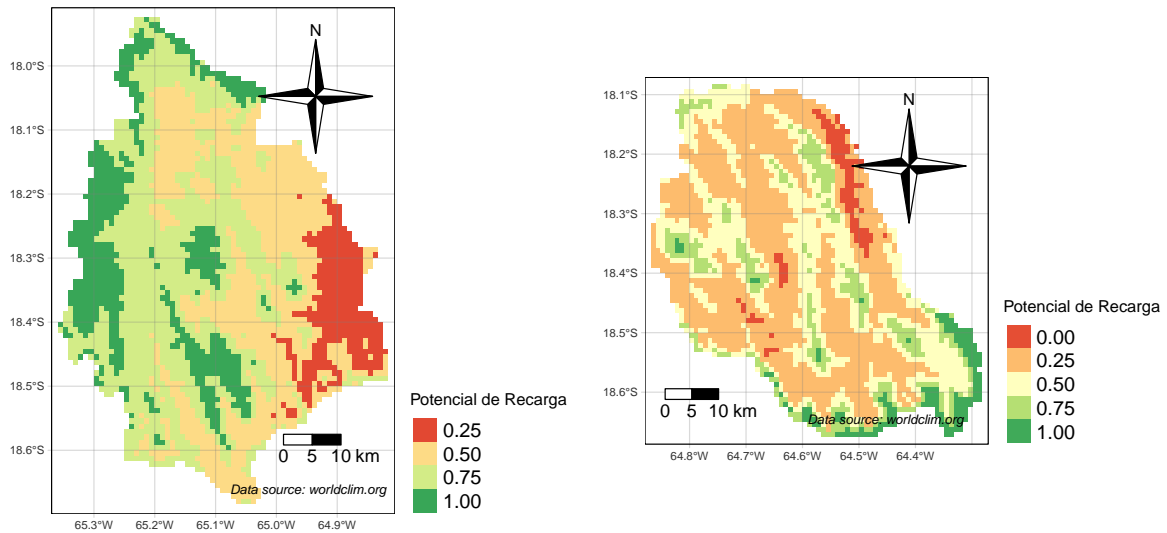


(a) Reclassified Precipitation Data in Aiquile



(b) Reclassified Precipitation Data in Pasorapa

Figure 3.2: Reclassification Result of the Precipitation in Aiquile ans Pasorapa
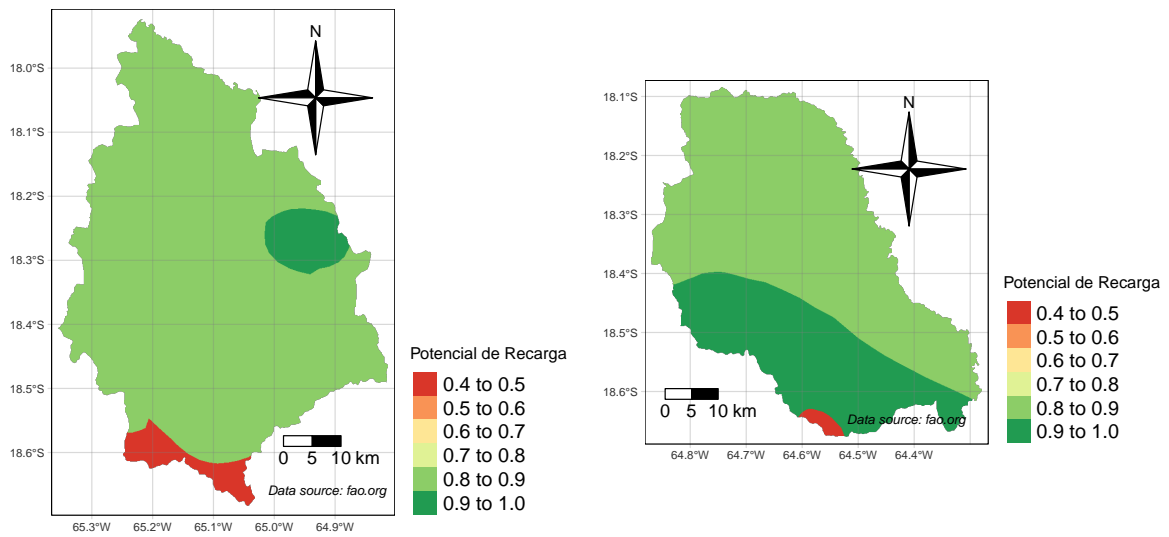
## 3.3 FAO Soil Type Data

The following FAO Soil Type Data available at fao.com contains Shapes in five different Categories. These have been assigned to a certain degree of Permeability of Water in (%). The Reclassification has been processed according to these values. The Code used can be seen in the Appendix.

Table 3.4: Reclassification table of the FAO Soil Type Data for Aiquile

| from | to | becomes | Class | FAOSOIL |
|---|---|---|---|---|
| 1 | 1 | 0.8 | Jordovician-Silurian and Devonian elastic rocks | Bk2-b |
| 1 | 2 | 0.8 | Paleozoic elastic rocks | I-Bd-Bh-c |
| 2 | 3 | 0.8 | Paleozoic elastic rocks | I-Be-Lc-c |
| 3 | 4 | 1.0 | Quaternary unconsolidateddeposits with much volcanicmaterial, ashes and outflows, Ordovician-Silurian clasticrocks | I-Tv-c |
| 4 | 5 | 0.4 | Ordovician-Silurian and Devonian clastic rocks | Lc6-c |

Table 3.5: Reclassification table of the FAO Soil Type Data for Pasorapa

| from | to | becomes | Class | FAOSOIL |
|---|---|---|---|---|
| 1 | 1 | 1.0 | Permo-Carboniferous one Tertiary elastic rocks | Bk2-b |
| 1 | 2 | 0.8 | Paleozoic elastic rocks | I-Bd-Bh-c |
| 2 | 3 | 0.8 | Devonian clastic rocks | Lc2-3b |
| 3 | 4 | 0.4 | Ordovician-Silurian and Devonian clastic rocks | Lc6-c |

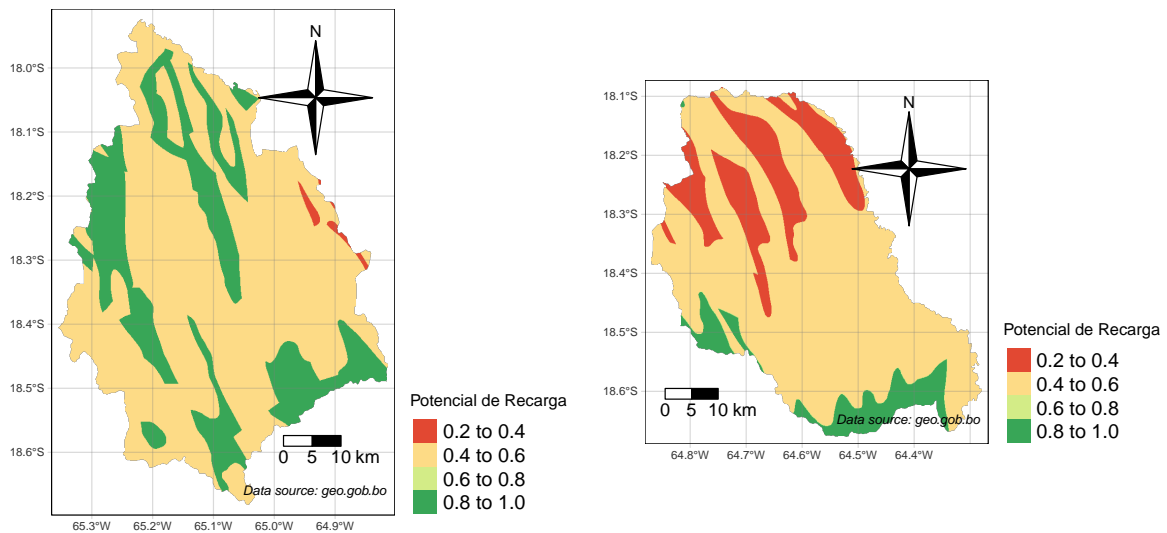(a) Reclassified FAO Soil Type Data in Aiquile    (b) Reclassified FAO Soil Type Data in Pasorapa

Figure 3.3: Reclassification Result of the FAO Soil Type Data in Aiquile

## 3.4 Geology Data

The following Geology data contains Shapes in six different Categories. The Categories has been assigned to a certain degree of Permeability in (%). The Reclassification has been processed according to these values. The Code used can be seen in the Appendix.

Table 3.6: Reclassification table of the Geology Data

| from | to | becomes | Class |
|------|-----|---------|-------|
| 1 | 1 | 0.2 | Crystalline |
| 1 | 2 | 0.4 | Deposits or Duricrust |
| 2 | 3 | 1.0 | Karst |
| 3 | 4 | 0.4 | Quarternary |
| 4 | 5 | 0.8 | Organic or Overburden |
| 5 | 6 | 0.8 | Sedimentary |



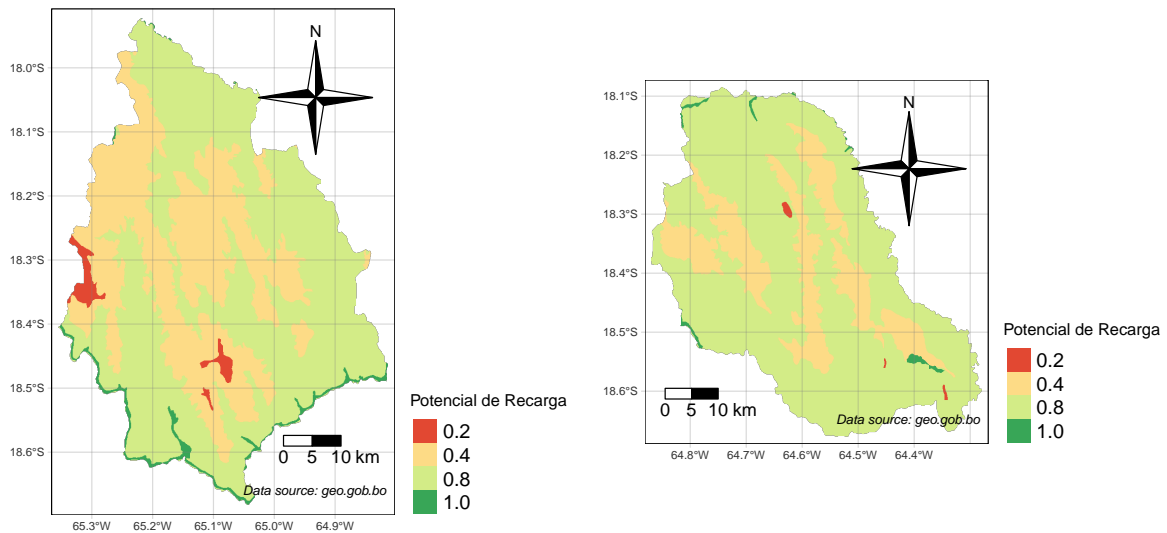(a) Reclassfied Geology Data in Aiquile     (b) Reclassfied Geology Data in Pasorapa

Figure 3.4: Reclassification Result of the Geology Data in Aiquile and Pasorapa

## 3.5 Vegetation Data

The following Vegetation data contains Shapes in four different Categories. The Vegetation has been categorized into a certain degree of Permeability in (%). The Reclassification has been processed according to these values. The code used for the reclassification can be seen in the Appendix.

Table 3.7: Reclassification Result of the Vegetation Data in Aiquile

| from | to | becomes | Class |
|---|---|---|---|
| 1 | 3 | 1.0 | Phreatophytic forests |
| 3 | 5 | 0.8 | Inter-Andean and sub-Andean xerophytic forests |
| 5 | 11 | 0.4 | Montane scrubland |
| 11 | 14 | 0.2 | Montane grassland / altimontane grasslands |



(a) Reclassfied Vegetation Data in Aiquile  (b) Reclassfied Vegetation Data in Pasorapa

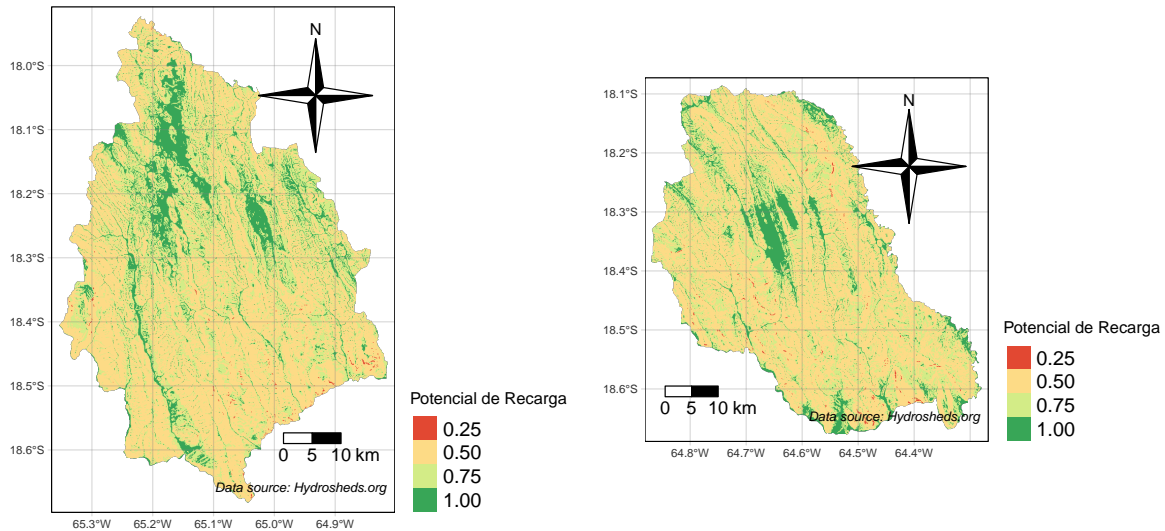Figure 3.5: Reclassification Result of the Vegetation Data in Aiquile

## 3.6 DEM Data

The provided Digital Elevation Model (DEM) consists of raster values showcasing variations in Aiquile's altitude, ranging from a minimum of 1231 to a maximum of 3450 meters, while Pasorapa's altitudes vary between a minimum of 926 and a maximum of 3063 meters above sea level. These altitude values were converted into slope data using the `terra::terrain` function from the Terra package.

Subsequently, the slope data was categorized into varying degrees of permeability (in %), as defined by Ernesto et al. (2021). The reclassification process was conducted based on these assigned values. For a detailed view of the reclassification code, please refer to the Appendix.

Table 3.8: Reclassification Table of the DEM Data

| from | to | becomes | Class |
|---:|---:|---:|---|
| 0 | 6 | 1.00 | Flat to almost flat |
| 6 | 15 | 0.75 | Moderately undulating |
| 15 | 45 | 0.50 | Moderately wavy |
| 45 | 65 | 0.25 | Steep |
| 65 | Inf | 0.00 | Steeply sloping |



(a) Reclassfied DEM Data in Aiquile

(b) Reclassfied DEM Data in Pasorapa

Figure 3.6: Reclassification Result of the DEM Data in Aiquile and Pasorapa
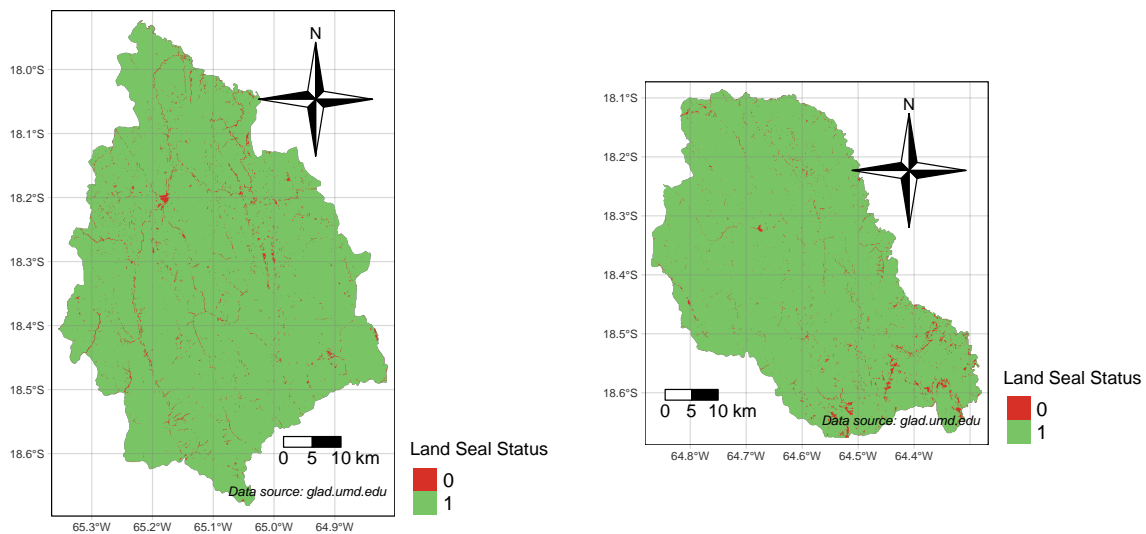
## 3.7 Land Use Data

The free to access GLAD dataset tracks changes in forests, croplands, urban areas, water bodies, and snow/ice cover globally from 2000 to 2020 at a high 30-meter resolution. Created using advanced machine learning tools, each aspect is validated separately.

The built-up land category includes man-made surfaces for infrastructure, commercial, and residential use. Using the CNN (U-Net) algorithm with Open Street Map data, the global built-up areas in 2000 and 2020 have been mapped. Validation data refined the depiction of these extents and changes over time.

The initial dataset encompassed three distinct values, which were subsequently transformed into two categories through a reclassification procedure assessing permeability. The reclassification table, served as the framework for this transformation. The code used for the reclassification can be seen in the Appendix.

Table 3.9: Reclassification Result of the Land Use Data in Aiquile

| from | to | becomes | Class |
|---|---|---|---|
| 0 | 1 | 1 | Not Sealed |
| 1 | 2 | 0 | Sealed |



(a) Reclassified Land Use Data in Aiquile      (b) Reclassified Land Use Data in Pasorapa

Figure 3.7: Reclassification Result of the Land Use Data in Aiquile and Pasorapa

# 4 Discussion

The following project has been conducted by following a unique approach in order to produce the most insightfull and easy to understand product possible. The final coloring and hierarchically structuring of the final four classes have been ordered according to the unique values the analysis has been produced.

These results are reasonable, since the variables that best explain water infiltration according to this method are, precisely, low slopes and high vegetation cover. In contrast, the areas classified with low recharge probability values mostly coincide with steep slopes, poor vegetation cover, and unfavorable land uses.

The study area analysis, based on field observations, revealed that potential groundwater recharge zones, as per the Matus (2007) method, predominantly existed within Eucalyptus forests. The introduction of non-native species like Eucalyptus is a common land use practice globally, aiming to enhance environmental benefits. However, concerns have been raised regarding adverse effects, notably water loss in the basin's hydrological balance, water repellency in soils, increased evapotranspiration, and reduced groundwater recharge and river discharge rates due to the deep-rooted nature of these species Rodriguez-Levy et al. (2023).

There are several examples of the benefits of floristic characteristics on the storage and infiltration of water (Ramírez et al. 2018; Bonnesoeur, Locatelli, and Ochoa-Tocachi 2019; Ellison et al. 2017; Le Maitre, Scott, and Colvin 1999), but more recently, a more critical vision has been adopted in which various elements of the vegetation cover are considered factors to the detriment of groundwater recharge (Blanco 2017; Acharya et al. 2018; Ilstedt et al. 2016).

In contributing to the ongoing scientific discussion on water management in Bolivia, I present a new perspective in this work by suggesting a unique approach involving personalized weighting and reclassification parameters. My proposed weighting system aims to readjust the importance assigned to specific variables or factors within our models.

To enhance the precision of our models, it's crucial to further evaluate this readjustment based on empirical insights and observations from the studied environments. By fine-tuning these weights it is possible to align our models more closely with the intricate realities of these ecosystems, potentially revealing details that might have been missed in previous analyses.

In proposing these tailored weighting and reclassification parameters, my goal is to aid the scientific conversation by introducing a more refined perspective. This approach provides a clearer lens through which diverse dynamics of our natural environments can be explored, understood and communicated.

# 5 Results

This study aimed to identify potential aquifer recharge zones in the Canton of Aiquile´s located in the State of Cochabamba (Bolivia). By exploring various geospatial datasets, including terrain attributes, geological features, vegetation patterns, land use, precipitation records, soil classifications by the FAO, and satellite-derived NDVI. Each dataset was analyzed using predetermined weights, emphasizing their relative importance in the study.

In conducting this Multicriteria Analysis, the numerous Raster and Vector Layers were integrated, using weighted factors to delineate optimal areas for natural water recharge zones (Spanish: *Zonas de Recarga Hídrica*). The project utilized the R-Studio Environment, leveraging key packages crucial for these calculations.

This resultant raster (Figure 5.2 and Figure 5.3) encapsulates a comprehensive representation of the region's environmental aspects, depicting their intricate interplay. The methodology seeks to identify aquifer recharge zones considering Pasorapa's unique characteristics. It aims to support local policymaking, drawing from Matus (2007) adaptable approach. The code used for the reclassifications and weightings can be seen in the Appendix. The final Raster Calculation is being conducted according to the following table.

| Weight | Data |
|---:|---|
| 0.25 | DEM |
| 0.15 | Geology |
| 0.05 | Vegetation |
| 0.10 | Land Use |
| 0.10 | Precipitation |
| 0.10 | Soil Type by the FAO |
| 0.25 | Satellite-born NDVI |

Figure 5.1: Final Weightings for the Reclassification

The following Map shows the potential of water-recharge across Aiquile according to the previous settings and classificacions in four different Classes: "Very low", "low", "Moderate" and "High". Code used for the visualizations can be seen in the Appendix.

To ensure an balanced visualization of the four recharge potential categories, subtle adjustments in breaks and labels were implemented in the final classification, evenly distributing the

data into four equally sized segments. These distinctions stem from the diverse geographic and contextual factors observed across both analyzed locations. Specifically, when delineating regions denoted as having 'high water recharge potential' in Aiquile, the last break is 4 percent higher compared to Pasorapa. This variance primarily results from Aiquile's relatively higher precipitation levels and more favorable geological conditions compared to Pasorapa.

The differences in break points highlight the nuanced nature of geographical features, environmental factors, and location-specific characteristics. The nuances discussed in the visualization aim to aid in interpreting the data, offering contextually relevant insights tailored to each distinct area. This approach facilitates the identification of pertinent regions for further conservation policy actions.
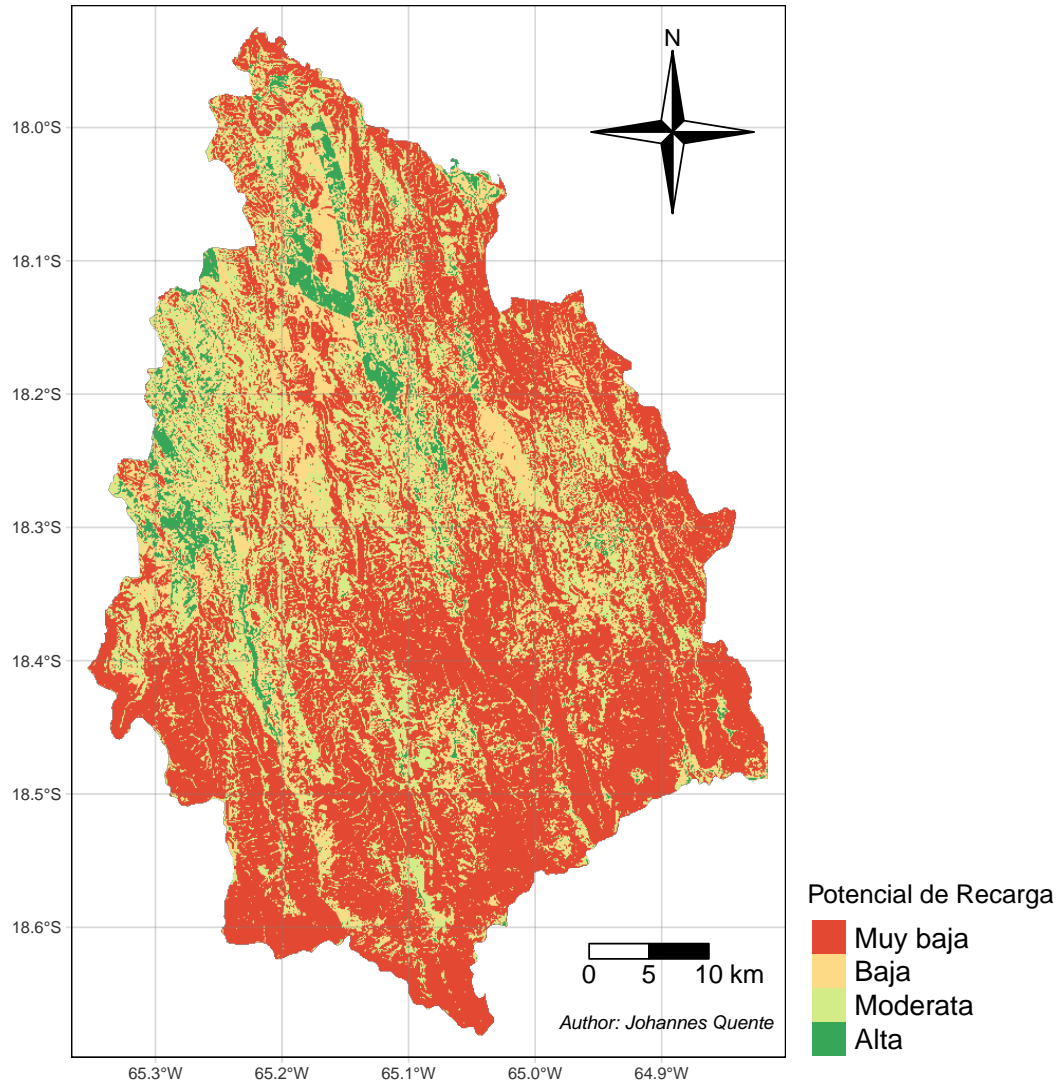
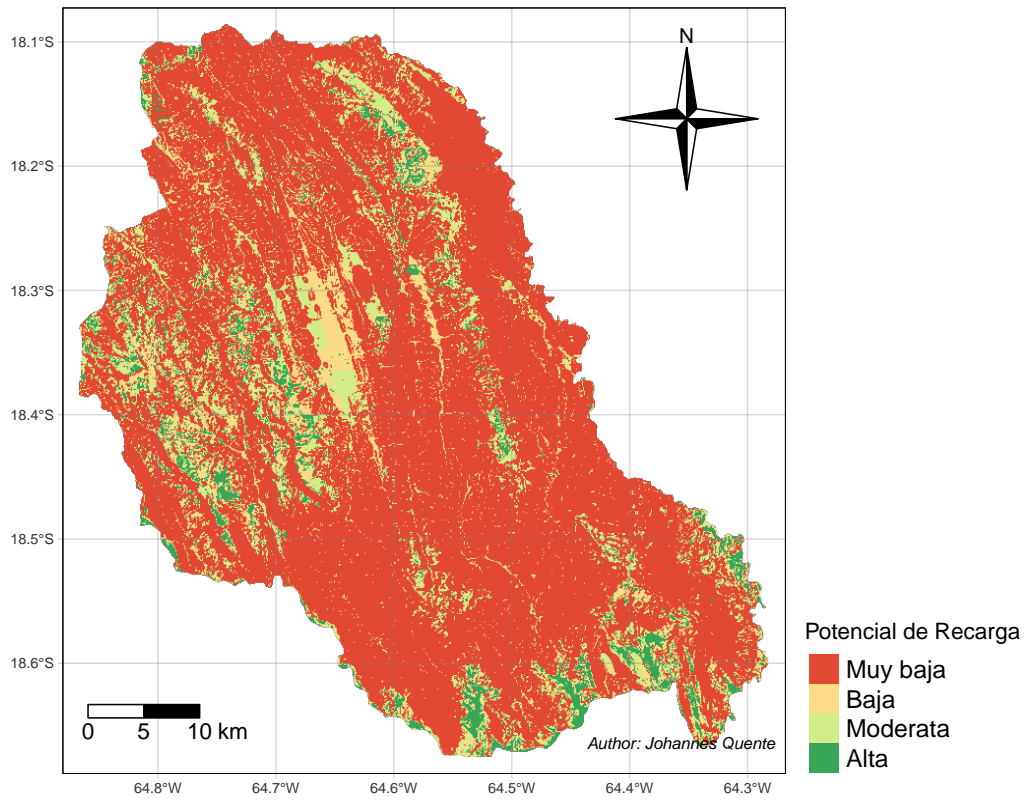Figure 5.2: Reclassified and Weighted Result in Aiquile

Figure 5.3: Reclassified and Weighted Result in Pasorapa

# 6 Summary

This study introduced an adjusted methodology to identify potential groundwater recharge zones in the Aiquile and Pasorapa municipalities in Bolivia. Initial analysis uncovered discrepancies in parameters proposed by Matus (2007), prompting a comprehensive reassessment of both original and recent variables (Ernesto et al. 2021). The study emphasized the impact of soil cover types, notably vegetation, revealing their significant influence on aquifer recharge. Notably, the crucial step of reclassifying land cover categories derived from Satellite Data emerged as pivotal in effectively delineating these recharge zones.

Insights gleaned from this study provide a foundation for crafting public policies aimed at safeguarding groundwater and recharge areas within these municipalities. The study underscored the critical role of ecosystem conservation, particularly native plant communities, in preserving surface biophysical properties and aquifer recharge potential. These areas hold considerable ecological, scientific, and cultural value, contributing to the natural heritage of Aiquile and Pasorapa.

While the study aimed to develop a tailored methodology for identifying groundwater recharge zones within the Virvini micro-basin, it recommends further analysis due to existing limitations, particularly involving ground truthing.

The practical implications of these findings are immediate, establishing crucial technical groundwork for future policies directed at protecting groundwater recharge zones in Aiquile and Pasorapa. These results represent the initial strides towards the long-term management of groundwater resources in this region.

Moreover, this work adds to the ongoing scientific discourse on water management in Bolivia by introducing a distinctive approach involving personalized weighting and reclassification parameters. By recalibrating the significance of specific variables within our models based on empirical insights, this approach seeks to refine our analyses and offer a more precise perspective to unravel the complexities of natural environments.

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# Appendix

## R-Studio Libraries

```r
# libraries used
library(raster)
library(terra)
library(ggplot2)
library(tmap)
library(sf)
library(dplyr)
library(tibble)
library(knitr)
library(webshot2)
```

## Reading Data

```r
# Read data and crop to Aiquile
# read data

## shapes
bol <- read_sf("gadm41_BOL_3.shp") # Aiquile extent
# veg <- read_sf("veg_nv_bol_geo.shp") # Vegetation
# geo <- read_sf("Geologia.shp") # Geografia
geo   <- read_sf("Geologia.dbf")   # Geografia

dsmw  <- read_sf("DSMW.shp",crs = 4326)

# other kind of vegetation
se_bo_geo <- read_sf("se_bo_geo.shp")

# precipitacion
precip01 <- rast("wc2.1_30s_prec_01.tif")
```

```r
precip02 <- rast("wc2.1_30s_prec_02.tif")
precip03 <- rast("wc2.1_30s_prec_03.tif")
precip04 <- rast("wc2.1_30s_prec_04.tif")
precip05 <- rast("wc2.1_30s_prec_05.tif")
precip06 <- rast("wc2.1_30s_prec_06.tif")
precip07 <- rast("wc2.1_30s_prec_07.tif")
precip08 <- rast("wc2.1_30s_prec_08.tif")
precip09 <- rast("wc2.1_30s_prec_09.tif")
precip10 <- rast("wc2.1_30s_prec_10.tif")
precip11 <- rast("wc2.1_30s_prec_11.tif")
precip12 <- rast("wc2.1_30s_prec_12.tif")

## raster
dem <- rast("s20w070_dem.tif")

# Land Use
land <- rast("Change_10S_070W.tif")
```

## Data Processing

```r
# Filter, crop and mask raster
# filter der bol shapes
aiquile   <- bol %>% filter(NAME_3 == "Aiquile")

# write_sf(aiquile, "aiquile.shp")

# DEM
##  crop and mask dem
dem_crop <- terra::crop(dem, aiquile)
dem_mask <- mask(dem_crop, aiquile)

# land
##  crop and mask dem
land_crop <- terra::crop(land, aiquile)
land_mask <- mask(land_crop, aiquile)


### Intersections Geo, Veg, se_bo_geo
# GEO
```

```r
# crop and mask geo
sf_use_s2(FALSE) # quick fix
geo_intersect  <- sf::st_intersection(geo, aiquile)


# Digital Soil Map of the World

dsmw_intersect  <- sf::st_intersection(dsmw, aiquile)


# se_bo_geo
se_bo_geo_intersect  <- sf::st_intersection(se_bo_geo, aiquile)
```

## Vegetation Indices calculation

```r
# Band Calc
# Set Color Bands 1
green_band  <- rast("LM05_L1TP_232073_19860801_20200831_02_T2_B1.TIF")
# green wavelenght range of 500-600 nanometers.
red_band    <- rast("LM05_L1TP_232073_19860801_20200831_02_T2_B2.TIF")
# red wavelength range, around 600-700 nanometers.
nir_band    <- rast("LM05_L1TP_232073_19860801_20200831_02_T2_B3.TIF")
# near-infrared light, approximately in the range of 700-1100 nanometers.
swir_band   <- rast("LM05_L1TP_232073_19860801_20200831_02_T2_B4.TIF")
# combination of visible and shortwave-infrared wavelengths.

# Set Color Bands 2
green_band_1  <- rast("LM05_L1TP_232072_19860801_20200831_02_T2_B1.TIF")
# green wavelenght range of 500-600 nanometers.
red_band_1    <- rast("LM05_L1TP_232072_19860801_20200831_02_T2_B2.TIF")
# red wavelength range, around 600-700 nanometers.
nir_band_1    <- rast("LM05_L1TP_232072_19860801_20200831_02_T2_B3.TIF")
# near-infrared light, approximately in the range of 700-1100 nanometers.
swir_band_1   <- rast("LM05_L1TP_232072_19860801_20200831_02_T2_B4.TIF")
# combination of visible and shortwave-infrared wavelengths.

# Calculate NDVI
ndvi <- (nir_band - red_band) / (nir_band + red_band)

# Calculate NDVI
ndvi_1 <- (nir_band_1 - red_band_1) / (nir_band_1 + red_band_1)
```

```r
# merge the raster
ndvi_full <- merge(ndvi, ndvi_1)

  # writeRaster(ndvi_full, "ndvi_full.tif")

# Transform the SpatRaster to the CRS of the polygon
# ndvi_same_crs <- project(ndvi_full, crs(aiquile))
    ndvi_wgs84  <- project(ndvi_full, "EPSG:4326")

# Aplicar las operaciones crop y mask
  ndvi_crop <- terra::crop(ndvi_wgs84, aiquile)
  ndvi_mask <- mask(ndvi_crop, aiquile)
```

## Reclassification NDVI-Index

```r
# Reclass
# Create a tibble with the reclassification table
reclass_table_indice <- tribble(
  ~from, ~to, ~becomes,
  -Inf, 0, 0.2,
  0, 0.05, 0.4,
  0.05, 0.2, 0.6,
  0.2, Inf, 1
)

# Reclassify the slope raster based on the reclassification table
ndvi_reclassified <- terra::classify(ndvi_mask,
reclass_table_indice,
include.lowest = TRUE, right = TRUE)

# Adding a new column C to the data frame
reclass_table_indice$Class <- c("Very Low", "Low", "Moderate", "High")
```

## Processing Precipitation

```r
# LOOP
# Crear una lista con los nombres de los objetos
lista_precip <- paste0("precip", sprintf("%02d", 1:12))
# Genera los nombres de precip01 a precip12

# Inicializar una lista vacía para almacenar los resultados
lista_precip_mask <- list()

# Iterar sobre cada objeto y aplicar las operaciones
for (i in seq_along(lista_precip)) {
  # Acceder al objeto con el nombre correspondiente
  precip_obj <- get(lista_precip[i])

  # Aplicar las operaciones crop y mask
  precip_crop <- terra::crop(precip_obj, aiquile)
  precip_mask <- mask(precip_crop, aiquile)

  # Almacenar el resultado en la lista
  lista_precip_mask[[i]] <- precip_mask
}

# Use the first raster as a base for the sum
sum_raster <- lista_precip_mask[[1]]

# Loop through the remaining rasters and add their values to the sum_raster
for (i in 2:length(lista_precip_mask)) {
  sum_raster <- sum_raster + lista_precip_mask[[i]]
}

# Create a tibble with the reclassification table
reclass_table_precip <- tribble(
  ~from, ~to, ~becomes,
  650,    Inf, 1,        # 650 to Inf becomes 1
  600,    650, 0.75,     # 600 to 650 becomes 0.75
  550,    600, 0.5,      # 550 to 600 becomes 0.5
  500,    550, 0.25,     # 500 to 550 becomes 0.25
  -Inf,   500, 0         # -Inf to 500 becomes 0
)
```

```r
# Assuming you have a slope raster 'slope_raster'
# Reclassify the slope raster based on the reclassification table
precip_reclassified <- classify(sum_raster,
reclass_table_precip, include.lowest = TRUE, right = TRUE)
```

## Reclass FAO Soil Type Data

```r
# Create an empty raster to rasterize into
empty_raster <- raster(extent(dsmw_intersect),
                resolution = c(0.0008333333, 0.0008333333))

# Convert SIMBOLO to factor
dsmw_intersect$FAOSOIL <- as.factor(dsmw_intersect$FAOSOIL)

# Rasterize
fao_raster <- rasterize(dsmw_intersect, empty_raster, field = "FAOSOIL")

# writeRaster(geo_raster, "geo_raster.tif", overwrite=TRUE)

# vis
# plot(geo_raster)

# reclass
# Create a tibble with the reclassification table
reclass_table_fao <- tribble(
  ~from, ~to, ~becomes,
  1, 1, 0.6,
  1, 2, 0.6,
  2, 3, 0.6,
  3, 4, 0.8,
  4, 5, 0.4
)

# Reclassify the slope raster based on the reclassification table
fao_reclassified <- reclassify(fao_raster, reclass_table_fao,
include.lowest = TRUE, right = TRUE)
```

## Reclass Geology Data

```r
# Create an empty raster to rasterize into
empty_raster <- raster(extent(geo_intersect),
                resolution = c(0.0008333333, 0.0008333333))

# Convert SIMBOLO to factor
geo_intersect$SIMBOLO <- as.factor(geo_intersect$SIMBOLO)

# Rasterize
geo_raster <- rasterize(geo_intersect, empty_raster, field = "SIMBOLO")

# reclass
# Create a tibble with the reclassification table
reclass_table_geo <- tribble(
  ~from, ~to, ~becomes,
  1, 1, 0.2,
  # C - Crystalline: Crystalline rocks or materials, often
  # associated with igneous or metamorphic formations.
  1, 2, 0.4,
  # D - Duricrust: Hard layer formed on the ground by cementation.
  2, 3, 1,
  # K - Karst: Karst terrain, which is characterized by soluble
  # bedrock, such as limestone, and features like caves and sinkholes.
  3, 4, 0.4,
  # Q - Quarternary: Geological or environmental classification
  # related to the Quaternary period.
  4, 5, 0.8,
  # O - Organic materials or overburden, referring to
  # unconsolidated material covering bedrock.
  5, 6, 0.8,
  # S - Sedimentary: Sedimentary rocks or materials.
)

# Assuming you have a slope raster 'slope_raster'
# Reclassify the slope raster based on the reclassification table
geo_reclassified <- reclassify(geo_raster, reclass_table_geo,
                    include.lowest = TRUE, right = TRUE)
```

## Reclass Vegetation Data

```r
# Create an empty raster to rasterize into
empty_raster <- raster(extent(se_bo_geo_intersect),
                       resolution = c(0.0008333333, 0.0008333333))

# Rasterize
veg_bol <- rasterize(se_bo_geo_intersect, empty_raster)

# reclass
# Create a tibble with the reclassification table
reclass_table_veg <- tribble(
  ~from, ~to, ~becomes,
  1, 3, 1,
  # Bosques freatófitos / Phreatophytische Wälder
  3, 5, 0.8,
  # Bosques xerofíticos interandinos y subandinos
  # / Inter- und subandine xerophytische Wälder
  5, 11, 0.4,
  # matorral pluvial montano / montanes Pluvialgebüsch
  11, 14, 0.2,
  # matorral pluvial montano pastizal montano altimontano
  # / altimontanes montanes Grasland
)

# Reclassify the slope raster based on the reclassification table
veg_reclassified <- reclassify(veg_bol, reclass_table_veg,
                     include.lowest = TRUE, right = TRUE)
```

## Reclass DEM Data

```r
## slope calculation with the function terra::terrain()
terrain  <- terrain(dem_mask)

# Create a tibble with the reclassification table
reclass_table_dem <- tribble(
  ~from, ~to, ~becomes,
  0, 6, 1,            # Class 1: Plano a casi plano
  6, 15, 0.75,        # Class 2: Moderadamente ondulado
```

```
  15, 45, 0.5,        # Class 3: Ondulado/cóncavo
  45, 65, 0.25,       # Class 4: Escarpado
  65, Inf, 0          # Class 5: Fuertemente escarpado
)


# Reclassify the slope raster based on the reclassification table
dem_reclassified <- classify(terrain, reclass_table_dem,
include.lowest = TRUE, right = TRUE)
```

## Reclass Land Use Data

```
legend_labels <- c("1" = "Sealed", "0" = "Not Sealed")

# Create a tibble with the reclassification table
reclass_table_land <- tribble(
  ~from, ~to, ~becomes,
  0, 1, 1,
  1, 2, 0,
)


# Reclassify the slope raster based on the reclassification table
land_reclassified <- classify(land_mask, reclass_table_land,
include.lowest = TRUE, right = TRUE)
```

## Final Raster Calculation and Weighting

```
# Align resolutions (resample veg)
veg_resampled <- resample(veg_spatraster, dem_reclassified)

# Align resolutions (resample geo)
geo_reclassified <- resample(geo_reclassified, veg_resampled)

# Align resolutions (resample land)
land_reclassified <- resample(land_reclassified, geo_reclassified)

# Align resolutions (resample land)
precip_reclassified <- resample(precip_reclassified, land_reclassified)
```

```r
# Align resolutions (resample land)
fao_reclassified <- resample(fao_reclassified, precip_reclassified)

# Align resolutions (resample land)
ndvi_reclassified <- resample(ndvi_reclassified, fao_reclassified)

# ZR (zona de recarga) = [0.27*(Pend)+0.23*(Ts)+0.12*(Tr)+0.25*(Cve)+0.13* (Us)]

# Adjusted weights
weight_dem     <- 0.25
weight_geo     <- 0.15
weight_veg     <- 0.05
weight_land    <- 0.1
weight_precip <- 0.1
weight_fao     <- 0.1
weight_sat     <- 0.25

# Perform the adjusted weighted combination
final_raster <- weight_dem     * dem_reclassified +
                weight_geo     * geo_reclassified +
                weight_veg     * veg_resampled +
                weight_land    * land_reclassified +
                weight_precip * precip_reclassified +
                weight_fao     * fao_reclassified +
                weight_sat     * ndvi_reclassified
```

## Final Mapping Results

```r
#  breaks and labels for the reclassification: Aiquile
breaks <- c(0, 0.67, 0.7, 0.77, 1)
labels <- c("Muy baja", "Baja", "Moderata", "Alta")

#  breaks and labels for the reclassification: Pasorapa
breaks <- c(0, 0.67, 0.7, 0.73, 1)
labels <- c("Muy baja", "Baja", "Moderata", "Alta")

# change name
names(final_raster) <- "Potencial de Recarga"
```

```r
# Cut the raster values into categorical factors
factor_raster <- cut(values(final_raster), breaks = breaks,
labels = labels, include.lowest = TRUE)

# Use dplyr's recode to change the factor levels based on the breaks and labels

factor_raster <- factor_raster %>%
  recode("Muy baja" = "Alta", "Baja" = "Moderata",
         "Moderata" = "Baja", "Alta" = "Muy baja")

# Create a new raster with categorized values
r_categorized <- final_raster
values(r_categorized) <- as.character(factor_raster)

if (knitr::is_html_output()) {

# view
tmap_mode("view")

tm_shape(r_categorized, labels = "New Legend Label") +
    tm_raster(style = "cont", palette = "YlGn", breaks = breaks,
              labels = labels, alpha = 0.8) +
tm_basemap(c("Esri.WorldImagery", "OpenStreetMap.Mapnik")) +
  tm_minimap()

} else if (knitr::is_latex_output()) {

  # view
tmap_mode("plot")

tm_shape(r_categorized, labels = "New Legend Label") +
    tm_raster(style = "cont", palette = "YlGn", breaks = breaks,
              labels = labels, alpha = 0.8) +
      tm_scale_bar(breaks = c(0, 5, 10), text.size = 0.9) +
   tm_compass(type = "4star", size = 6, position = c("right", "top")) +
  tm_credits("Author: Johannes Quente", fontface = "italic", align = "right") +
  tm_graticules(alpha = 0.3) +
  tm_layout(
    legend.text.size = 1,
    legend.position = c("left", "bottom"),
    legend.outside = TRUE
```

```
    )
}
```