

## Drought vulnerability analysis using NDLI and strategy for mitigation in Tallo Watershed, Indonesia

Muh Iriansyah Akram<sup></sup>, Andang Suryana Soma<sup></sup>,  
and Baharuddin Baharuddin<sup></sup>

Department of Forestry, Faculty of Forestry, Hasanuddin University, Tamalanrea Campus,  
Jalan Perintis Kemerdekaan Km. 10, Makassar 90245, Indonesia.

\*E-mail: s\_andangs@unhas.ac.id

Received: 25 August 2025 / Accepted: 02 April 2026 / Available online: 16 April 2026 Open



Access: This work is distributed under the Creative Commons Attribution 4.0 License.

### Abstract

Rapid land-cover change in Tallo Watershed, driven by urbanisation and population growth, has intensified environmental degradation. This has increased drought risk, particularly under ongoing climate change and growing pressure on water resources. This study aims to assess spatial drought conditions and formulate adaptive land-use directions in Tallo Watershed. Landsat 8 OLI/TIRS imagery from 2014 and 2023 was analysed using a band combination of SWIR-1 (band 6), NIR (band 5), and Red (band 4), and drought conditions were evaluated using Normalised Difference Latent Heat Index (NDLI) as primary spatial indicator. Standardised Precipitation Evapotranspiration Index (SPEI) was applied as a climatic classification framework to support interpretation of NDLI-derived drought severity. The results indicate a clear increase in drought-affected areas, reaching 1,253 ha between 2014 and 2023, with distinct spatial patterns across upstream, mid-stream, and downstream zones. Land-cover change was dominated by expansion of settlements (+1,964 ha) and reduction of rice fields (–1,699 ha), reflecting rapid urban development. Areas experiencing intensive land-cover conversion consistently corresponded with higher drought severity, highlighting strong influence of anthropogenic land transformation on drought dynamics. Compared with recent studies that primarily focus on meteorological drought indicators, this study demonstrates added value of integrating remote sensing-based NDLI for capturing spatial variations in drought linked to land-cover change. Based on drought levels and regional biophysical characteristics, adaptive land-use directives were developed to enhance resilience to climate change. Findings provide critical spatial information for watershed management and adaptive land-use planning in rapidly urbanising regions.

**Keywords:** climate change, drought vulnerability, land-use adaptation, remote sensing, urban watershed.

### Introduction

Urbanisation and population growth have increasingly altered land-cover patterns through socio-economic development and

rural–urban migration, particularly in rapidly growing cities (Wijayanti and Priyanto 2022, Kagabo et al. 2024). Accelerated urban expansion intensifies land demand and often leads to forest degradation and

land-use conversion (Yang et al. 2024). Such transformations, especially conversion of forested areas into agricultural, residential, and industrial land, are widely recognised as major drivers of drought due to their impacts on hydrological processes (Tran et al. 2019).

Land-cover change fundamentally alters watershed hydrology by reducing soil infiltration capacity and groundwater recharge, increasing surface runoff, and weakening evapotranspiration regulation by vegetation. These changes collectively reduce soil moisture availability and intensify drought conditions, particularly in rapidly urbanising watersheds (Banda et al. 2025). In this context, forest conversion initiates a cascade of hydrological responses that ultimately contribute to drought intensification.

Drought represents one of most severe impacts of climate change, threatening water availability, agricultural productivity, energy security, and ecosystem stability (Rahman et al. 2025). Globally, more than 40 % of the land area and approximately 30 % of the population are affected by drought, encompassing nearly 45 % of agricultural land worldwide (Ling et al. 2023). Forest conversion without sustainable management reduces soil infiltration capacity and increases surface runoff (Ilstedt et al. 2007), while increasing temperatures accelerate evapotranspiration, intensifying soil moisture deficits (Murray and Ebi 2012). These processes are further aggravated by excessive groundwater extraction in urban areas.

In Indonesia, groundwater depletion in major cities has reached critical levels due to declining recharge rates and increasing groundwater abstraction (Azis et al. 2015). South Sulawesi Province, particularly Makassar City – the largest metropolitan area in Eastern Indonesia – has

experienced continued population growth, increasing from 1.41 million in 2013 to 1.47 million in 2023 (BPS 2024). This demographic pressure has driven extensive land-use conversion and urban development, thereby elevating drought risk. Long-term analyses indicate that drought events in South Sulawesi occurred annually between 1999 and 2019, with an average annual occurrence rate of approximately 15.5 % (Utami et al. 2020).

Impacts of these dynamics are particularly evident in Tallo Watershed, which functions as critical environmental system for urban water resources in Makassar City. It is located predominantly in downstream section of watershed, and has undergone rapid land conversion, resulting in a substantial decline in forest cover. Recent studies indicate that forested areas account for only about 11 % of total watershed area, contributing to reduced water retention capacity between 2003 and 2022 (Fatiawan et al. 2024). Consequently, in 2023, local authorities declared a drought emergency after more than 5,100 households in the districts of Tallo, Tamalanrea, and Biringkanaya experienced severe shortages of clean water (CNN Indonesia 2023).

Reduction of green open spaces, which play vital role in enhancing soil water storage and infiltration, has further exacerbated drought vulnerability in Tallo Watershed (Chen et al. 2023). Recurrent drought impacts have heightened public concern across Makassar City and surrounding regions, highlighting urgent need for improved drought assessment, early warning systems, and adaptive watershed management strategies (Ling et al. 2023).

Despite increasing attention to drought issues in urban watersheds, most studies in Indonesia remain focused on meteo-

rological indices or administrative-scale analyses, with limited integration of spatially explicit vegetation-based drought indicators and adaptive land-use planning. International research has demonstrated the effectiveness of remotely sensed, vegetation-based indices for drought monitoring and environmental assessment at watershed and regional scales (Vicente-Serrano et al. 2010, Liou et al. 2019, Xu et al. 2021). However, such work largely emphasises drought detection and severity mapping, with relatively limited efforts to translate drought vulnerability information into spatially explicit land-use adaptation strategies, particularly in rapidly urbanising tropical watersheds. In Tallo Watershed, comprehensive analyses linking remotely sensed drought vulnerability with adaptive land-use directions remain scarce. This study addresses this research gap by assessing drought vulnerability using NDLI and formulating adaptive land-use directions to support drought mitigation and sustainable watershed management.

The objective of this study is to analyse drought conditions in Tallo Watershed using NDLI and derive adaptive land-use strategies to mitigate drought. Findings are expected to provide spatially explicit information on drought vulnerability, supporting evidence-based land-use planning and water resource management in rapidly urbanising watersheds.

## Materials and Methods

### Study area

Research was conducted in Tallo Watershed, geographically located between 119°26'57" E and 119°46'26" E, and between 5°6'7" S and 5°12'22" S, covering

an area of 43,665 ha. Administratively, Tallo Watershed borders Gowa Regency, Maros Regency, and Makassar City in South Sulawesi. The watershed flows from upstream mountains in Gowa Regency to the west, emptying into Makassar Strait (Fig. 1).

### Data collection

Data used in this study were initially prepared by defining boundaries of the research area, followed by pre-processing and processing stages. Research area was delineated using boundary data for Tallo Watershed obtained from SK.304/MENLHK/PDASHL/DAS.0/7/2018 concerning watershed determination. The watershed was then divided into three zones: upstream, midstream, and downstream. During pre-processing, Landsat 8 OLI imagery for 2014 and 2023 was downloaded. Bands were then merged, and imagery clipped to research area.

In the data processing stage, imagery was interpreted through manual digitisation and classification of land cover using Landsat 8 OLI data. This process produced land cover maps and detected changes between 2014 and 2023. Drought analysis was then performed using NDLI method, which employs Landsat 8 OLI imagery from 2014 and 2023 to assess water availability under drought conditions.

To assess reliability of 2023 land-use/land-cover (LULC) classification, accuracy assessment was conducted using a confusion-matrix approach. Validation was performed using 60 ground reference points from field observations to verify satellite image classification. Assessment yielded overall accuracy of 88 % and Kappa coefficient of 0.88, indicating high level of agreement between classified map and

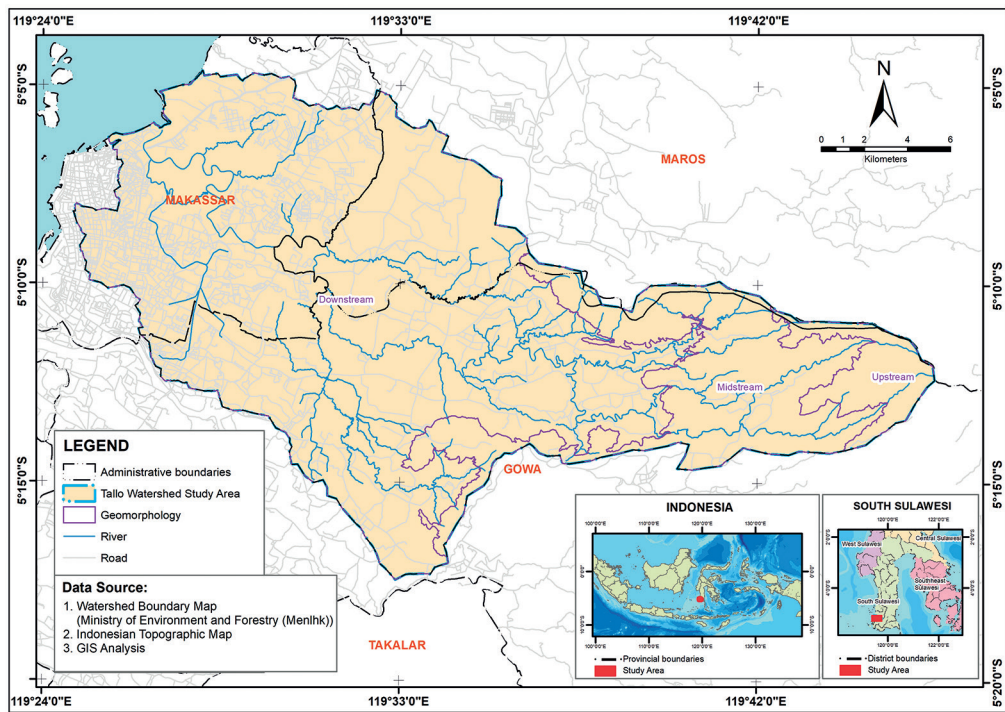


Fig. 1. Map of the research location.

reference data. These results confirm that 2023 LULC map is sufficiently accurate for subsequent drought vulnerability analysis.

Image interpretation generated maps of land-cover change and drought levels in Tallo Watershed. These datasets were overlaid with Regional Spatial Plans (RTRW) of Gowa Regency, Maros Regency, and Makassar City using GIS-based approach. Area function zoning (protected and cultivation areas) and spatial pattern allocations were extracted from RTRW maps to assess land-use suitability. This overlay analysis was used to derive adaptive land-use directions for drought mitigation, considering drought severity, regional functional suitability, and designated spatial patterns within watershed.

Data analysis

Radiometric correction

Radiometric correction was performed to address disturbances caused by atmospheric conditions, sensor characteristics, and illumination variations in Landsat images, ensuring resulting reflectance values accurately represent surface conditions (Jaya et al. 2022). Correction was applied using FLAASH algorithm, based on MODTRAN 4 radiative transfer model. Procedure included radiometric calibration, determination of sensor parameters and image metadata, and enabled accurate estimation of water vapour and aerosols from sensor perspective (Chakouri et

al. 2020, Muna et al. 2020). Reflectance values of corrected image are constrained within range  $0 \leq \rho \leq 1$ , as defined by piecewise function (1):

$$\rho = \begin{cases} 0, & \text{if } b_1 \leq 0 \\ 1, & \text{if } b_1 \geq 10000 \\ \frac{b_1}{10000} & 0 < b_1 < 10000 \end{cases} \quad (1)$$

where:  $\rho$  is image reflectance value (dimensionless), and  $b_1$  is digital number of image band being corrected.

Landsat 8 OLI/TIRS Collection 2 surface reflectance imagery, atmospherically corrected, was used to identify drought conditions. Drought assessment was performed using green (band 3), red (band 4), and shortwave infrared (SWIR, band 6) spectral bands (Liou et al. 2019).

### LULC change

For land-cover analysis, Landsat 8 OLI/TIRS imagery from 2014 and 2023 was used with band combination assigning SWIR-1 (band 6) to red, NIR (band 5) to green, and red (band 4) to blue to produce false-colour images highlighting vegetation close to natural colours (Kosasih et al. 2019). Imagery was cropped to boundaries of research area. Interpretation was performed through manual digitisation, employing unsupervised classification based on hue, colour, shape, and texture. Land cover was analysed based on classified images, and results were validated using Indonesian terrain maps. Overlay analysis was then performed to compare changes in area between 2014 and 2023 using GIS. Data were subsequently processed in pivot tables using .dbf attribute files.

### NDLI

NDLI monitors vegetation health, soil moisture, and surface water availability. In this study, it was primary index used to quantify spatial drought conditions in Tallo Watershed. All spatial drought analyses were conducted exclusively using NDLI values derived from Landsat imagery. It was calculated using atmospherically corrected Landsat 8 OLI/TIRS Collection 2 imagery, employing green (band 3), red (band 4), and SWIR (band 6) bands. Band 3 (0.533–0.590  $\mu\text{m}$ ) is sensitive to chlorophyll and vegetation water content, band 4 (0.636–0.673  $\mu\text{m}$ ) responds strongly to vegetation and can distinguish between open land and vegetation experiencing water stress. Band 6 (1.566–1.651  $\mu\text{m}$ ) is sensitive to water content in soil and leaves; its reflectance decreases under high water-content conditions, making it effective for differentiating dry soil from water-saturated soil (Liou et al. 2019).

NDLI estimates water availability on vegetation and soil surfaces using bands 3, 4, and 6 of the spectrum, and thereby indicates heat energy flux at Earth's surface. This analysis is expressed by equation (2) (Liou et al. 2019):

$$\text{NDLI} = \frac{\rho_3 - \rho_4}{\rho_3 + \rho_4 + \rho_6}, \quad (2)$$

where:  $\rho_3$ ,  $\rho_4$ , and  $\rho_6$  are surface reflectance values of band 3 (green), band 4 (red), and band 6 (SWIR), respectively.

In addition to remote sensing-based NDLI, Standardised Precipitation Evapotranspiration Index (SPEI) was employed to analyse meteorological drought intensity. SPEI was used solely as supporting climatic information to aid interpretation and classification of NDLI-derived drought severity, and was not involved in NDLI

calculation. SPEI is particularly effective for climate change studies, as it accounts for both precipitation and potential evapotranspiration (PET) (Vicente-Serrano et al. 2010). PET was estimated using Thornthwaite equation. Monthly water balance  $D_i$  equation (3):

$$D_i = P_i - PET_i, \quad (3)$$

where:  $P_i$  is precipitation (mm) and  $PET_i$  is potential evapotranspiration (mm).

Resulting  $D_i$  values were fitted to log-logistic probability distribution, transforming data into standardised distribution and allowing comparison of drought severity across different time scales (Beguería et al. 2014). SPEI-based drought classification is presented in Table 1. It should be emphasised that SPEI classification does not replace NDLI as primary drought indicator, and no mathematical conversion was applied between NDLI and SPEI.

**Table 1. Classification of SPEI.**

| Range index   | Class            |
|---------------|------------------|
| $\geq 1$      | Extremely wet    |
| 0.5 – 0.99    | Very wet         |
| 0.1 – 0.49    | Wet              |
| 0 – 0.09      | Slight wet       |
| -0.09 – -0.01 | Moderate drought |
| -0.1 – -0.49  | Drought          |
| -0.5 – -0.89  | Severe drought   |
| $\leq -0.9$   | Extreme drought  |

Land-use directions for drought mitigation were developed through GIS-based spatial integration of environmental vulnerability and regional planning frameworks. This methodology comprised three main components: (1) drought severity maps derived from SPEI and NDLI analyses, (2) existing land-cover data, and (3) official Regional Spatial Plans (RTRW) of Makassar City, Gowa Regency, and Maros Regency.

Combining NDLI with SPEI-based classification and GIS spatial integration aligns with recent advances in vegetation- and energy-based drought assessment, particularly in urban and tropical watershed contexts (Liou et al. 2019, Chen et al. 2023, Huang et al. 2025).

Spatial overlay analysis was conducted to identify priority zones for drought mitigation across Tallo Watershed. Zones were further classified based on watershed morphology into upstream, midstream, and downstream segments to support site-specific mitigation strategies. Land-use suitability was assessed according to area functions and spatial pattern classifications regulated under Government Regulation No. 26 of 2008, as summarised in Table 2.

Adaptive land-use directives were derived following Technical Guidelines for the Internalisation of Watershed Management Plans into Regional Spatial Plans (PDASHL 2018). NDLI-based drought severity maps were overlaid with land-use/land-cover data and area function zoning (RL, RK, RP, PL, PB) using a GIS-based approach.

Tallo Watershed was divided into upstream, midstream, and downstream zones to enable spatially differentiated adaptation strategies. Overlay analysis grouped drought adaptation measures into vegetative rehabilitation (VEG) and civil engineering techniques (ST). Vegetative measures were prioritised in upstream zones to enhance infiltration and soil moisture retention. Downstream zones emphasised civil engineering measures and urban green infrastructure to reduce surface runoff and mitigate drought impacts. This approach resulted in spatially explicit land-use direction patterns (VEG I–III and ST I–III), as summarised in Table 3.

**Table 2. Suitability of area functions and space patterns.**

| Area function                                                                      | Spatial patterns | Spatial pattern area | Coding |
|------------------------------------------------------------------------------------|------------------|----------------------|--------|
| Protected forest                                                                   | Protected areas  | Protected forest     | RL     |
|                                                                                    | Cultivation area | Protected forest     |        |
| Production forests, Limited production forests, and Convertible production forests | Protected areas  | PF, LPF, CPF         | RP     |
|                                                                                    | Cultivation area | PF, LPF, CPF         |        |
| Conservation areas                                                                 | Protected areas  | Conservation areas   | RK     |
|                                                                                    | Cultivation area | Conservation areas   |        |
| Other use areas                                                                    | Protected areas  | Protective OLUA      | PL     |
|                                                                                    | Cultivation area | OLUA cultivation     | PB     |

Source: Regulation of Directorate General of Watershed Management and Protected Forests (2018). Legend: PF – production forest, LPF – limited production forest, CPF – convertible production forest, OLUA – other land use area.

**Table 3. Spatial land-use direction coding (VEG/ST) according to drought class and watershed zone.**

| Drought class                  | Watershed zone |               |              |
|--------------------------------|----------------|---------------|--------------|
|                                | Downstream     | Midstream     | Upstream     |
| Moderate drought               | VEG II, ST III | VEG II, ST II | VEG II       |
| Drought                        | VEG II, ST III | VEG II, ST II | VEG II, ST I |
| Severe drought/Extreme drought | VEG II, ST III | VEG II, ST II | VEG I, ST I  |

Note: VEG I–III indicate increasing levels of vegetative rehabilitation, while ST I–III represent increasing levels of civil engineering interventions. Levels are assigned according to drought severity and watershed zone. Source: Regulation of Directorate General of Watershed Management and Protected Forests (2018).

## Results and Discussion

### LULC change

Changes LULC reflect spatial dynamics of human activities and ecosystem transformations within watershed. It changes, including forests, agricultural land, and settlements, between 2014 and 2023 were assessed using Landsat 8 OLI imagery (path 114, row 63).

Table 4 and Figure 2 present LULC change matrix from 2014 to 2023, analysed according to regional morphology (upstream, midstream, and downstream) within Tallo Watershed. This analysis reveals patterns of land conversion reflecting intensive development pressure and land-use change, particularly in downstream areas.

Low-density dryland forest (HKR) remained relatively stable, occupying 1,827.72 ha. Meanwhile, plantation forest (HT) decreased, partially converting into HKR. Other LULC categories showed minimal change, indicating low anthropogenic pressure in upstream region.

Forest conversion was more extensive in the midstream region. HKR was largely converted into mixed dryland agriculture with shrubs (PLKCS; 165.05 ha), paddy fields (SW; 17.82 ha), and shrubland (SB; 102.43 ha). Conversely, SB was converted into rainfed agriculture (PLK; 317.77 ha), PLKCS (68.09 ha), and paddy fields (SW; 45.34 ha). Conversion of PLKCS into settlements (11.21 ha) indicates rising pressure from agricultural expansion and residential development,

Table 4. Land-use/land-cover (LULC) change matrix, in ha.

| Watershed zone | LULC 2014 | LULC 2023 |       |         |        |       |        |           |           |         |          |         |         | Total area |           |
|----------------|-----------|-----------|-------|---------|--------|-------|--------|-----------|-----------|---------|----------|---------|---------|------------|-----------|
|                |           | A         | B     | HKR     | HMR    | HT    | LT     | PM        | PLK       | PLKCS   | SW       | SB      | BR      |            | TM        |
| Upstream       | HKR       |           |       | 1827.72 |        |       |        |           |           |         | 0.84     | 2.44    |         |            | 1831.01   |
|                | HT        |           |       | 17.06   |        | 22.12 |        |           |           |         |          |         |         |            | 39.18     |
|                | PM        |           |       |         |        |       |        | 0.51      |           |         |          |         |         |            | 0.51      |
|                | PLKCS     |           |       |         |        |       |        | 0.19      |           | 27.15   |          |         |         |            | 27.35     |
|                | SW        |           |       |         |        |       |        | 0.32      |           | 2.33    | 27.35    |         |         |            | 29.99     |
|                | SB        |           |       |         |        |       |        |           |           |         |          | 3.29    |         |            | 3.29      |
| Midstream      | HKR       |           |       | 2016.30 |        | 1.10  |        |           | 6.06      | 165.05  | 17.82    | 102.43  |         |            | 2308.77   |
|                | HT        |           |       | 17.74   |        | 54.80 |        |           |           | 24.04   | 0.35     | 124.14  |         |            | 221.07    |
|                | PM        |           |       |         |        |       |        | 33.15     |           |         |          |         |         |            | 33.15     |
|                | PLK       |           |       |         |        |       |        | 0.04      | 602.01    | 140.20  |          | 9.94    |         |            | 752.19    |
|                | PLKCS     |           |       |         |        | 0.07  | 8.83   | 11.21     | 119.00    | 868.25  | 4.74     | 58.73   |         |            | 1070.84   |
|                | SW        |           |       | 11.24   |        |       |        | 5.11      | 79.92     | 23.82   | 538.08   | 58.78   |         |            | 716.95    |
|                | SB        |           |       | 3.76    |        |       | 15.08  | 1.81      | 317.77    | 68.09   | 45.34    | 2807.07 |         |            | 3258.92   |
| Downstream     | A         | 357.57    |       |         | 1.71   |       |        | 0.04      | 0.69      |         | 2.71     |         | 72.99   | 4.04       | 439.76    |
|                | B         |           | 87.15 |         |        |       |        |           |           |         |          |         |         |            | 87.15     |
|                | HKR       |           |       | 25.59   |        |       | 0.00   |           | 1.87      |         |          | 10.68   |         |            | 38.15     |
|                | HMR       |           |       |         | 132.67 |       |        |           |           | 0.18    |          | 0.44    | 33.71   | 3.88       | 192.61    |
|                | HT        |           |       |         |        | 5.85  |        |           |           | 14.53   |          | 16.79   |         |            | 37.17     |
|                | LT        |           |       |         |        |       | 1.12   | 23.91     | 23.80     | 2.27    | 0.00     | 8.85    | 1.85    |            | 61.80     |
|                | PM        |           |       |         |        |       |        | 9082.63   |           |         |          |         |         |            | 9082.63   |
|                | PLK       | 6.06      |       |         |        |       | 22.81  | 662.13    | 8559.09   | 725.11  | 548.38   | 38.43   | 6.35    |            | 10,568.36 |
|                | PLKCS     | 10.41     |       |         | 1.08   | 0.12  | 35.47  | 162.47    | 499.15    | 879.20  | 32.16    | 235.28  |         | 12.69      | 1868.02   |
|                | SW        | 96.08     |       |         |        |       | 15.75  | 863.39    | 726.70    | 72.77   | 5,654.87 | 341.98  | 176.69  | 24.90      | 7973.14   |
|                | SB        |           |       |         | 1.60   |       | 20.74  | 94.36     | 381.13    | 146.59  | 122.01   | 755.97  | 61.53   | 5.30       | 1589.23   |
|                | BR        |           |       |         |        |       |        | 15.84     | 0.10      | 4.40    | 12.42    | 18.42   | 115.91  |            | 167.08    |
| TM             | 2.10      |           |       | 6.45    |        | 34.94 | 101.60 |           |           | 13.82   | 18.10    | 15.74   | 1074.03 | 1266.77    |           |
| Total area     |           | 472.22    | 87.15 | 3919.42 | 143.51 | 82.96 | 155.85 | 11,080.45 | 11,317.29 | 3163.99 | 7020.89  | 4611.77 | 484.76  | 1124.84    | 43,665.10 |

Legend: PL – LULC, A – water bodies, B – airport, HKR – low-density dryland forest, HMR – low-density mangrove forest, HT – forest plantation, LT – bare land, PM – built-up area, PLK – rainfed agriculture, PLKCS – dryland agriculture mixed with shrubs, SW – paddy fields, SB – shrubland, BR – swamp shrubland, TM – pond.

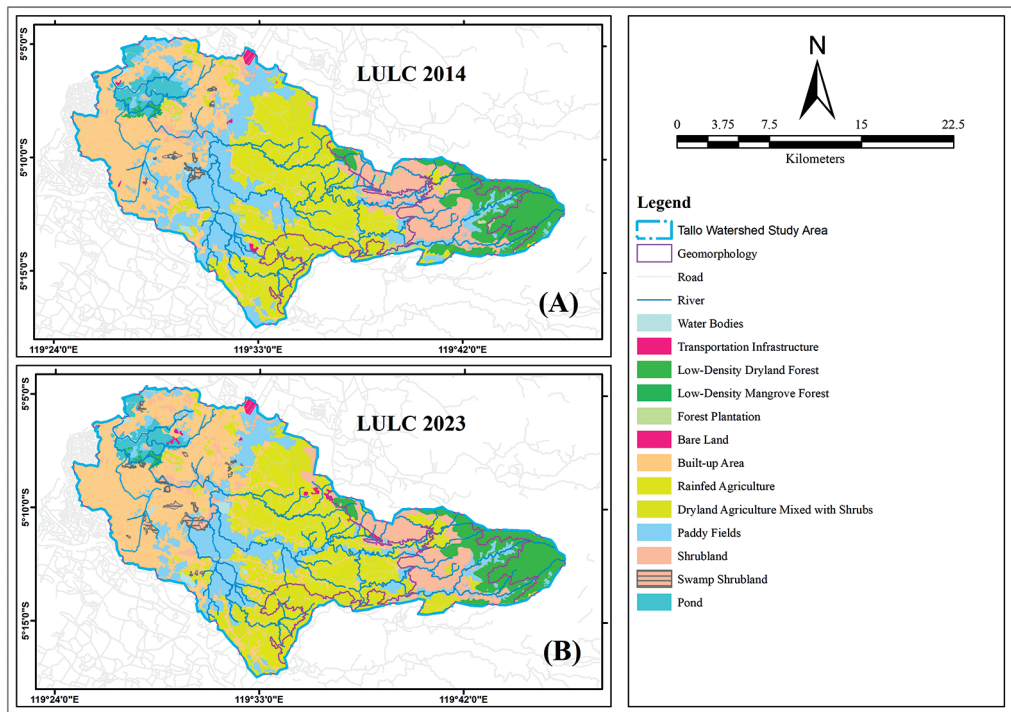


**Fig. 2. Land-use/land-cover (LULC) maps for 2014 and 2023.**

highlighting increasing stress on natural ecosystems.

The downstream region underwent most extensive LULC changes. Settlement expansion increased markedly, primarily through conversion of rainfed agriculture (PLK; 662.13 ha), PLKCS (162.47 ha), and paddy fields (SW; 863.39 ha). In addition, dryland farming expanded substantially, largely replacing rice fields, shrubland, and mixed dryland agriculture. These changes indicate intense urbanisation, land-use intensification, and altered ecosystem functions.

LULC change in Tallo Watershed is strongly influenced by population growth, economic pressure, and shifts in community lifestyles, particularly in rapidly urbanising river basin environments. Wittberg et al. (2025) highlighted that these factors

drive land conversion, typically transforming forested areas into settlements, agricultural land, and other built-up surfaces.

Unplanned LULC change has profound impact on watershed ecological functions (Baidoo and Obeng 2023). Agaton et al. (2016) reported that extensive agricultural expansion and accelerated settlement development, when exceeding environmental carrying capacity, disrupt watershed stability, resulting in declining water quality and increased hydrological risk. This aligns with Putra et al. (2024), who demonstrated that land-conversion-driven watershed degradation directly reduces water infiltration capacity and increases surface runoff.

The observed LULC dynamics confirm that urban expansion in Tallo Watershed is extensive, particularly concentrated

in downstream areas. Maheshwari et al. (2020) showed that urban-driven land-use change alters infiltration rates and evapotranspiration processes, triggering complex environmental feedbacks within watershed.

Furthermore, Fatiawan et al. (2024) concluded that LULC change in Tallo Watershed is closely linked to human activities aimed at meeting residential and livelihood needs. Nugroho et al. (2018) noted that land-use transformation reflects socio-economic demands, particularly population growth in urbanising watersheds. Additional drivers include spatial planning policies and weak regulatory enforcement (Anugraha et al. 2023), which facilitate land conversion even within protected or ecologically sensitive zones (Supriyanto et al. 2023).

NDLI

NDLI provides interpretation of latent heat flux, reflecting surface water availability and moisture conditions. NDLI values were used to distinguish areas with high water content from regions with low water content, where a value of +1 indicates high water availability and a value close to -1 indicates low availability. Spatial distribution of NDLI-derived conditions is shown in Figure 3 and classified based on SPEI to identify drought levels across Tallo Watershed. SPEI classification results are presented in Table 5.

As shown in Table 5, drought conditions in Tallo Watershed between 2014 and 2023 shifted clearly toward drier states. Areas in slightly wet category decreased by 1,433.50 ha, from 13,896.80 ha to

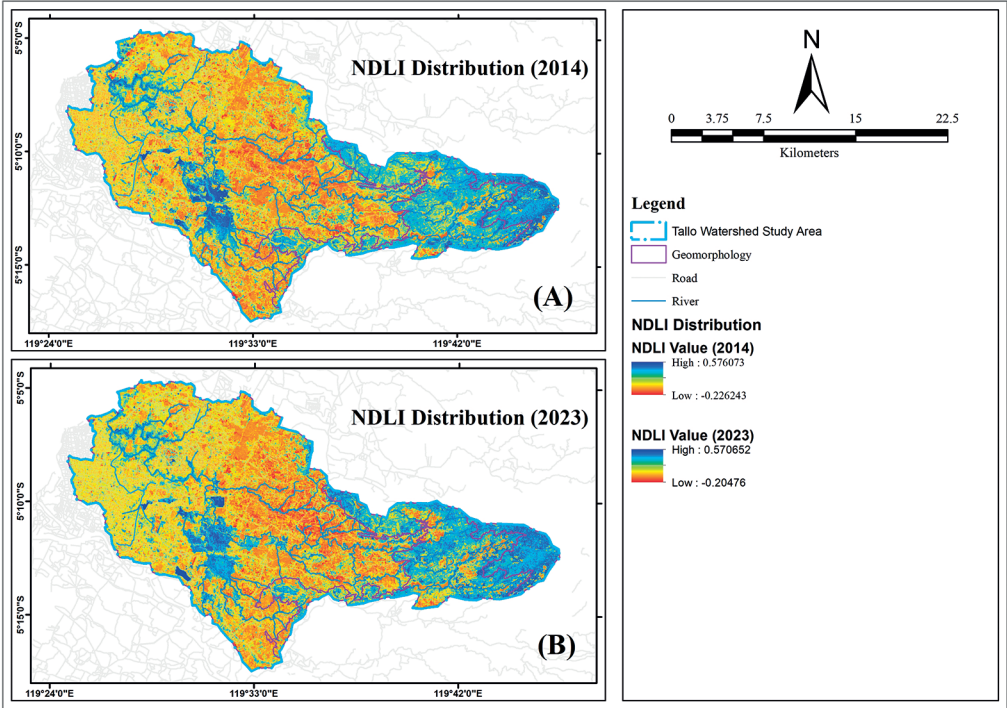


Fig. 3. Normalised Difference Latent Heat Index (NDLI) maps for 2014 and 2023.

**Table 5. Changes in area of SPEI-based drought classes in Tallo Watershed between 2014 and 2023.**

| SPEI range    | Class            | Area 2014, ha | Area 2023, ha | Change, ha |
|---------------|------------------|---------------|---------------|------------|
| $\geq 0.9$    | Extremely wet    | 0             | 0             | 0          |
| 0.5 – 0.89    | Very wet         | 0.21          | 0.24          | 0.03       |
| 0.1 – 0.49    | Wet              | 992.83        | 1173.59       | 180.76     |
| 0 – 0.09      | Slightly wet     | 13,896.80     | 12,463.30     | -1433.50   |
| -0.09 – -0.01 | Moderate drought | 28,611.31     | 29,582.83     | 971.52     |
| -0.5 – -0.10  | Drought          | 163.94        | 445.13        | 281.19     |
| -0.9 – -0.51  | Severe drought   | 0             | 0             | 0          |
| $\leq -1$     | Extreme drought  | 0             | 0             | 0          |

12,463.30 ha, while moderate drought areas increased by 971.52 ha, from 28,611.31 ha to 29,582.83 ha. Latter ones also expanded by 281.19 ha, from 163.94 ha to 445.13 ha. Although wet areas increased by 180.76 ha, from 992.83 ha to 1,173.59 ha, this was insufficient to offset overall drying trend.

Figure 4 illustrates spatial distribution of drought conditions in 2014 and 2023. In 2014, moderate drought was predominantly observed in central and southern parts of watershed, whereas upstream areas remained slightly wet to wet. A similar pattern persisted in 2023, with moderate drought dominating central and down-

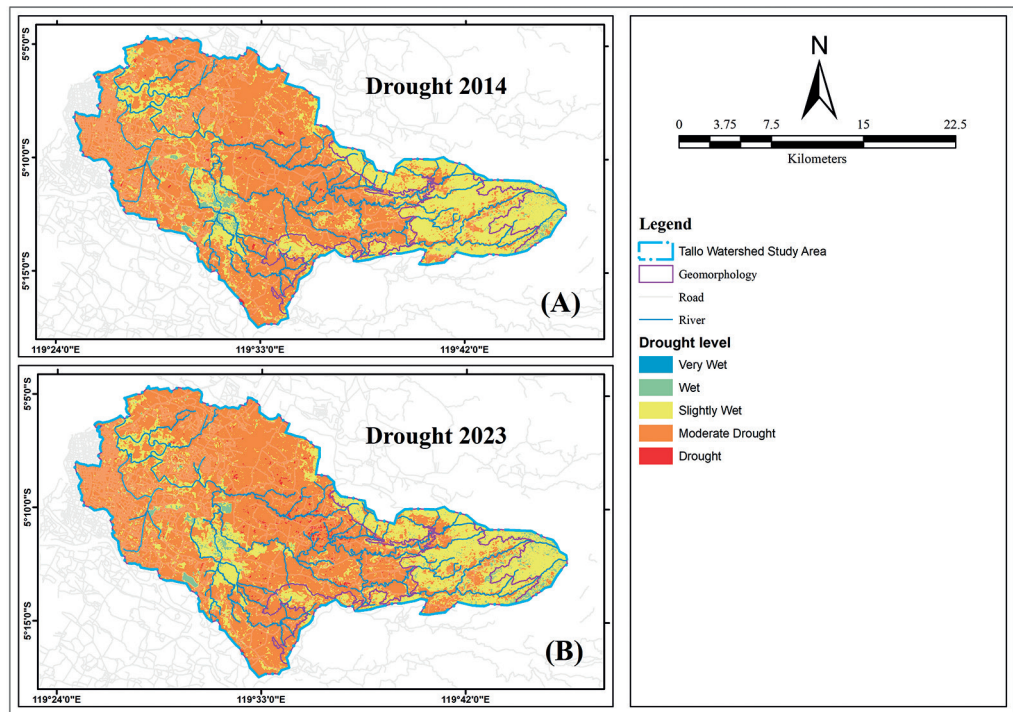


**Fig. 4. Drought maps of 2014 and 2023.**

stream areas of Gowa Regency, Makassar City, and Maros Regency, while upstream zones generally remained slightly wet to wet. This distribution highlights higher vulnerability of downstream areas, characterised by intensive land-cover change and rapid urbanisation, and provides basis for targeted water conservation, land rehabilitation, and climate change adaptation strategies in Tallo Watershed.

As indicated in Table 6, significant changes in drought classes occurred between 2014 and 2023. Most areas in moderate drought category remained unchanged, covering 25,790.80 ha, indicating persistent conditions. However, notable shifts were observed: approximately 377.18 ha transitioned from moderate drought to drought, while 2,340.35 ha improved to slightly wet conditions. Conversely, large areas previously slightly wet shifted to moderate drought, covering 9,568.79 ha. Smaller transitions from wet and very wet categories to drier classes were also recorded. Overall, these dynamics reflect changes in soil moisture driven by climatic variability and land-use change, highlighting key implications for water resource management and future drought mitigation in Tallo Watershed.

Based on NDLI analysis and SPEI classification, Tallo Watershed experienced clear shift towards drier conditions between 2014 and 2023. Slightly wet areas decreased by 1,433.50 ha,

from 13,896.80 ha to 12,463.30 ha, while moderate drought areas increased by 971.52 ha. Drought class also expanded by 281.19 ha, reflecting an overall intensification of drought conditions across watershed.

The drought level change matrix shows that most areas in moderate drought category remained unchanged in 2023 (25,790.80 ha), indicating persistent drought conditions over time. A substantial portion of areas previously slightly wet shifted to moderate drought (3,623.04 ha), reflecting progressive decline in soil moisture. Smaller transitions from wet and very wet categories to drier classes were also observed, but were spatially limited.

The observed shift toward drier conditions is consistent with recent studies employing vegetation- and energy-based drought indices in rapidly urbanising watersheds. Liou et al. (2019) and Xu et al. (2021) demonstrated that NDLI effectively captures reductions in latent heat flux associated with declining soil moisture and vegetation cover. Similar patterns have been reported in tropical watersheds undergoing rapid land-use conversion, particularly in downstream urban areas (Chen et al. 2023, Huang et al. 2025).

The magnitude of drought expansion in Tallo Watershed – particularly increase in moderate drought and drought classes between 2014 and 2023 – appears greater than in several comparable studies.

Table 6. Drought level change matrix, in ha.

|                    |                  | Drought level 2023 |                  |                |           |          | Total     |
|--------------------|------------------|--------------------|------------------|----------------|-----------|----------|-----------|
| Drought            |                  | Drought            | Moderate drought | Moderately wet | Wet       | Very wet |           |
| Drought level 2014 | Drought          | 38.47              | 120.93           | 4.54           | 0.01      | n.a.     | 163.94    |
|                    | Moderate drought | 377.18             | 25,790.80        | 2,340.35       | 102.97    | n.a.     | 28,611.31 |
|                    | Slightly wet     | 29.41              | 3,623.04         | 9,568.79       | 675.56    | n.a.     | 13,896.80 |
|                    | Wet              | 0.06               | 48.06            | 549.62         | 394.90    | 0.18     | 992.83    |
|                    | Very wet         | n.a.               | n.a.             | n.a.           | 0.15      | 0.05     | 0.21      |
| Total              |                  | Total              | 445.13           | 29,582.83      | 12,463.30 | 1,173.59 | 0.24      |

This pattern is likely driven by rapid reduction of green open spaces, high population density, and intensive groundwater abstraction in downstream urban areas of Makassar City. These findings highlight high vulnerability of urban tropical watersheds and underscore importance of integrating NDLI-based drought assessment with land-use planning and watershed management strategies. Importantly, while results are consistent with global NDLI-based drought studies, this research demonstrates how drought vulnerability information can be operationalised into spatially explicit land-use adaptation strategies at watershed scale – an aspect that remains limited in previous studies.

### Land-use directions

Land-use directions for upstream, mid-stream, and downstream segments of Tal-

lo Watershed were formulated as climate change adaptation strategies to mitigate drought impacts through integrated vegetative rehabilitation and civil engineering measures. These interventions aimed to enhance water storage capacity, maintain soil moisture, and restore vegetation cover, thereby strengthening watershed resilience to increasing drought pressure (Effiong et al. 2024).

### Upstream area

As shown in Table 7, land-use directions in upstream area primarily emphasise reforestation, agroforestry, and industrial plantation forests (HTI) across various land-cover types, including low-density dryland forest, dryland agriculture, shrubland, and paddy fields. Vegetative rehabilitation (VEG II) dominates this zone, reflecting its function as main water catch-

**Table 7. Land-use directives in upstream area.**

| LULC                             | Instruction code | Vegetation management direction                 | Civil engineering management direction   | Area, ha |
|----------------------------------|------------------|-------------------------------------------------|------------------------------------------|----------|
| HKR – low-density dryland forest | VEG II           | Agroforestry and community forest               | n.a.                                     | 3.15     |
|                                  |                  | Greening/non-timber production                  | n.a.                                     | 3.14     |
|                                  |                  | Reforestation/enrichment planting/Agroforestry  | n.a.                                     | 4.57     |
|                                  |                  | Reforestation and plantation forest development | n.a.                                     | 20.00    |
|                                  | VEG II, ST I     | Agroforestry and community forest               | Gully plug/Gully core/Individual terrace | 0.03     |
|                                  |                  | Reforestation and plantation forest development | Gully plug/Gully core/Individual terrace | 0.15     |
| HT – plantation forest           | VEG II           | Reforestation/enrichment planting/agroforestry  | n.a.                                     | 0.06     |
| PM – built-up area (settlement)  | VEG II           | Greening/non-timber production                  | n.a.                                     | 0.47     |
|                                  | VEG II, ST III   | Agroforestry and community forest               | Biopore absorption holes                 | 0.27     |

| LULC                                          | Instruction code | Vegetation management direction                 | Civil engineering management direction   | Area, ha |
|-----------------------------------------------|------------------|-------------------------------------------------|------------------------------------------|----------|
| PLKCS – dryland agriculture mixed with shrubs | VEG II           | Agroforestry and community forest               | n.a.                                     | 9.96     |
|                                               |                  | Greening/non-timber production                  | n.a.                                     | 1.87     |
|                                               |                  | Reforestation/enrichment planting/agroforestry  | n.a.                                     | 0.01     |
|                                               |                  | Reforestation and plantation forest development | n.a.                                     | 0.86     |
|                                               | VEG II, ST I     | Agroforestry and community forest               | Gully plug/Gully core/Individual terrace | 0.12     |
| SW – paddy fields                             | VEG II           | Agroforestry and community forest               | n.a.                                     | 0.57     |
|                                               |                  | Greening/non-timber production                  | n.a.                                     | 20.88    |
|                                               |                  | Reforestation/enrichment planting/agroforestry  | n.a.                                     | 0.12     |
|                                               |                  | Reforestation and plantation forest development | n.a.                                     | 0.30     |
| SB – shrubland                                | VEG II           | Agroforestry and community forest               | n.a.                                     | 1.72     |
|                                               |                  | Reforestation and plantation forest development | n.a.                                     | 0.37     |

ment area, characterised by steep topography and high infiltration potential.

Civil engineering measures (ST I), including gully plugs, gully cores, individual terraces, and biopore absorption holes, are selectively applied in settlement areas and mixed dryland agriculture to reduce erosion and enhance soil water retention. Largest priority areas include paddy fields (20.88 ha) and low-density dryland forest (20.00 ha), which play critical role in regulating surface runoff and maintaining slope stability.

The upstream area has undergone ecological degradation as a result of deforestation and land-use conversion. Consequently, land-use directions prioritise reforestation using native and locally adapted species (e.g., *Falcataria moluccana* (Miq.) Barneby & J.W. Grimes, *Swietenia macrophylla* King, and *Leucaena*

*leucocephala* (Lam.) de Wit), integrated with soil and water conservation measures. These interventions are intended to restore hydrological functions, enhance infiltration capacity, and reduce drought vulnerability in the upper watershed.

### Midstream area

In midstream segment, land-use directions are uniformly implemented under VEG II and ST II codes, integrating diversified vegetative rehabilitation with moderate civil engineering interventions. As shown in Table 8, largest priority areas for rehabilitation are concentrated in rain-fed agriculture (602.11 ha), paddy fields (378.88 ha), and shrubland (219.24 ha).

Adaptation strategies in this zone prioritise agroforestry systems that integrate perennial trees (e.g., *Tectona grandis* L.f.,

**Table 8. Vegetation management direction by LULC (midstream segment).**

| LULC                                          | Vegetation management direction                 | Area, ha |
|-----------------------------------------------|-------------------------------------------------|----------|
| HKR – low-density dryland forest              | Agroforestry and community forest               | 18.70    |
|                                               | Greening/non-timber production                  | 17.58    |
|                                               | Reforestation/enrichment planting/agroforestry  | 71.51    |
| HT – plantation forest                        | Reforestation and plantation forest development | 1.70     |
| LT – open land                                | Agroforestry and community forest               | 3.49     |
|                                               | Greening/non-timber production                  | 18.49    |
|                                               | Reforestation/enrichment planting/agroforestry  | 0.10     |
| PM – built-up area (settlement)               | Agroforestry and community forest               | 36.64    |
|                                               | Greening/non-timber production                  | 9.00     |
| PLK – rainfed agriculture                     | Agroforestry and community forest               | 602.11   |
|                                               | Greening/non-timber production                  | 279.60   |
|                                               | Reforestation/enrichment planting/agroforestry  | 141.48   |
| PLKCS – dryland agriculture mixed with shrubs | Agroforestry and community forest               | 293.62   |
|                                               | Greening/non-timber production                  | 70.68    |
|                                               | Reforestation/enrichment planting/agroforestry  | 233.99   |
| SW – paddy fields                             | Agroforestry and community forest               | 71.81    |
|                                               | Greening/non-timber production                  | 378.88   |
|                                               | Reforestation/enrichment planting/agroforestry  | 40.72    |
| SB – shrubland                                | Agroforestry and community forest               | 50.25    |
|                                               | Greening/non-timber production                  | 237.62   |
|                                               | Reforestation/enrichment planting/agroforestry  | 219.24   |

*Gliricidia sepium* (Jacq.) Kunth ex Walp., *Leucaena leucocephala*) with seasonal crops such as maize, groundnuts, and sweet potatoes. This approach improves soil structure, enhances soil moisture retention, and increases agricultural productivity while providing diversified livelihoods for local communities. Civil engineering measures, including non-structural drainage, gully terraces, individual terraces, and bench terraces, support efficient surface water management and reduce drought sensitivity.

### Downstream area

Downstream segment, which includes Makassar City, represents most drought-vulnerable zone due to high population density, extensive built-up areas, and low infiltration capacity. As presented in Table 9, land-use directions cover large areas of settlements (10,210.68 ha), dryland agriculture (9,349.33 ha), and paddy fields (4,290.84 ha), all of which are assigned to VEG II and ST III directive codes.

**Table 9. Land-use guidelines in downstream area.**

| <b>LULC</b>                                   | <b>Vegetation Management Direction</b>          | <b>Area, ha</b> |
|-----------------------------------------------|-------------------------------------------------|-----------------|
| A – water bodies                              | Greening/non-timber production                  | 15.53           |
|                                               | Agroforestry and community forest               | 29.72           |
| B – airport                                   | Agroforestry and community forest               | 86.10           |
| HKR – low-density dryland forest              | Greening/non-timber production                  | 0.30            |
|                                               | Agroforestry and community forest               | 11.34           |
| HMR – low-density mangrove forest             | Greening/non-timber production                  | 7.08            |
|                                               | Reforestation and plantation forest development | 0.85            |
| LT – open land                                | Agroforestry and community forest               | 99.88           |
|                                               | Greening/non-timber production                  | 29.60           |
| PM – built-up area (Settlement)               | Agroforestry and community forest               | 10,210.68       |
|                                               | Greening/non-timber production                  | 194.83          |
| PLK – rainfed agriculture                     | Agroforestry and community forest               | 9,349.33        |
|                                               | Greening/non-timber production                  | 174.37          |
|                                               | Reforestation/enrichment planting/agroforestry  | 14.89           |
|                                               | Agroforestry and community forest               | 1,142.50        |
| PLKCS – dryland agriculture mixed with shrubs | Greening/non-timber production                  | 47.17           |
|                                               | Reforestation/enrichment planting/agroforestry  | 75.43           |
| SW – paddy fields                             | Agroforestry and community forest               | 4,290.84        |
|                                               | Greening/non-timber production                  | 97.81           |
|                                               | Reforestation/enrichment planting/agroforestry  | 2.47            |
|                                               | Agroforestry and community forest               | 558.57          |
| SB – shrubland                                | Greening/non-timber production                  | 95.11           |
|                                               | Reforestation/enrichment planting/agroforestry  | 8.69            |
| BR – swamp shrubland                          | Agroforestry and community forest               | 155.65          |
|                                               | Greening/non-timber production                  | 5.85            |
| TM – pond                                     | Agroforestry and community forest               | 396.47          |
|                                               | Greening/non-timber production                  | 61.10           |

Adaptation measures in this zone emphasise optimisation of urban green infrastructure and micro-scale water management technologies, including infiltration wells, biopores, individual drainage systems, and rainwater harvesting. Vegetative rehabilitation through non-timber production, agroforestry, and reforestation is applied across residential, agricultural, and pond areas to reduce evapotranspi-

ration and increase soil water storage. These measures aim to stabilise urban hydrological functions and ensure water availability during prolonged dry periods.

### **Synthesis of land-use directions**

Overall, land-use directions across three watershed zones demonstrate integrated approach to addressing land degrada-

tion, water scarcity, and climate change impacts. Each zone applies adaptive strategies tailored to its geomorphological characteristics and land-use dynamics, ranging from catchment restoration in up-stream area to urban water conservation in downstream area.

Importantly, this study translates ND-LI-based drought vulnerability assessments into spatially explicit, zone-specific land-use adaptation strategies at watershed scale. This operational linkage between drought indices and land-use planning remains limited in previous studies and represents key scientific contribution to management of urban tropical watersheds. Detailed maps of vegetative and civil engineering interventions are presented in Figure 5.

# Conclusions

This study confirms that land-cover change has significantly influenced spatial distribution and intensity of drought in Tallo Watershed. Conversion of forested areas into agricultural, residential, and industrial land has altered watershed hydrological processes by reducing infiltration and groundwater recharge while increasing surface runoff, resulting in lower soil moisture availability and higher drought severity in urbanising zones.

NDLI derived from Landsat imagery effectively captured spatial drought patterns and proved suitable for assessing drought conditions at watershed scale. SPEI was used as climatic classification framework to support interpretation of NDLI-based

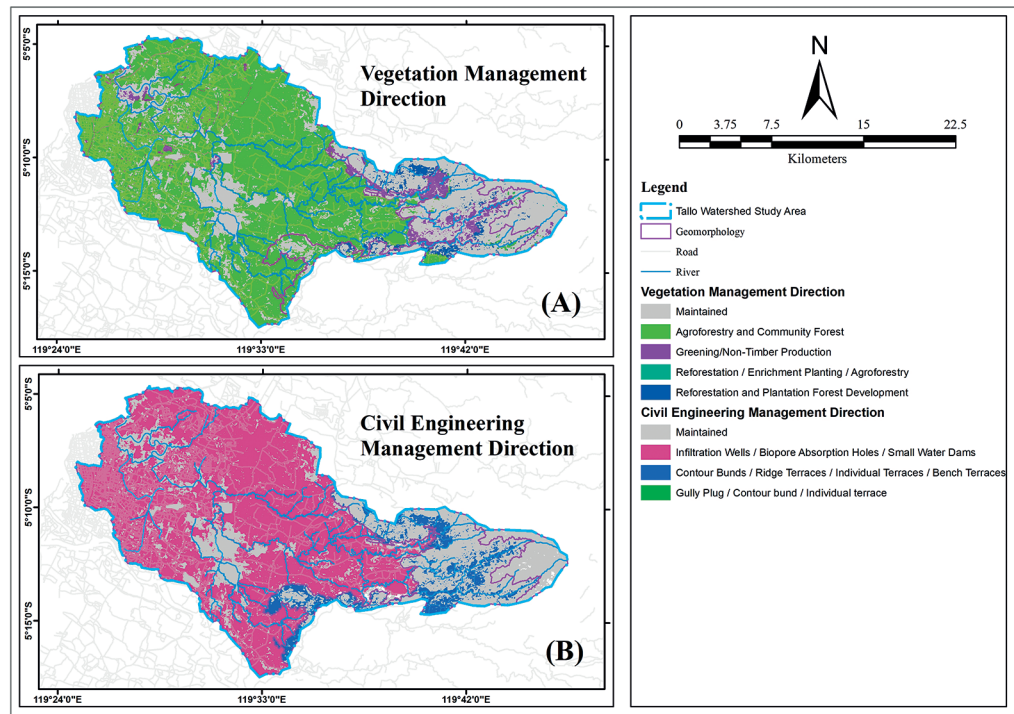


Fig. 5. Land-use direction maps: (A) vegetative measures; (B) civil engineering measures.

drought severity, enabling integration of meteorological context without altering NDLI-based analytical approach.

Results highlight that drought dynamics in study area are shaped not only by climatic variability but also by land-use change. Areas experiencing intensive land conversion consistently exhibited higher drought vulnerability. These findings underline importance of incorporating land-cover management into drought mitigation strategies. From policy perspective, protecting hydrologically functional land cover and integrating remote sensing based drought monitoring into watershed and urban planning can support more effective drought risk reduction and climate adaptation efforts.

## Acknowledgements

We would like to express our deepest gratitude to all parties who contributed to implementation of this research. We are sincerely grateful to the Faculty of Forestry at Hasanuddin University for the support and facilities provided during research process. We would also like to thank our colleagues who have cooperated, provided valuable assistance, and meaningful moral and technical support in completing this research.

## References

- AGATON M., SETIAWAN Y., EFFENDI H. 2016. Land use/land cover change detection in an urban watershed: A case study of Upper Citarum watershed, West Java Province, Indonesia. *Procedia Environmental Sciences* 33: 654–660. <https://doi.org/10.1016/j.proenv.2016.03.120>
- ANUGGRAH D.R., MUBARRAK M.Z., PAMBUDI W.A., SULILO J. 2023. Analisis permasalahan tata ruang di Indonesia. *Jurnal Multidisiplin Adijaya* 1(5): 1045–1051 (in Indonesian). <https://e-journal.naureendigiton.com/index.php/jam/article/view/867>
- AZIS A., YUSUF H., FAISAL Z., SURADI M. 2015. Water turbidity impact on discharge decrease of groundwater recharge in recharge reservoir. *Procedia Engineering* 125: 199–206. <https://doi.org/10.1016/j.proeng.2015.11.029>
- BAIDOO R., OBENG K. 2023. Evaluating the impact of land use and land cover changes on forest ecosystem service values using Landsat dataset in the Atwima Nwabiagya North, Ghana. *Heliyon* 9(11), e21736. <https://doi.org/10.1016/j.heliyon.2023.e21736>
- BANDA K., SHILENGWE C., NYAMBE I. 2025. Integrating environmental and LULC drivers of groundwater droughts in groundwater-dependent ecosystems: A machine learning (XGBoost)-SEM analysis with ecosystem implications. *Ecol Process* 14, 64. <https://doi.org/10.1186/s13717-025-00633-w>
- BEGUERÍA S., VICENTE-SERRANO S.M., REIG F., LATORRE B. 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology* 34(10): 3001–3023. <https://doi.org/10.1002/joc.3887>
- BPS 2024. Statistik Daerah Provinsi Sulawesi Selatan 2024. Badan Pusat Statistik, Jakarta. <https://sulsel.bps.go.id/id/publication/2024/09/26/4cfb630a2a0ff6ee14c3d45c/statistik-daerah-provinsi-sulawesi-selatan-2024.html>
- CHAKOURI M., LHISSOU R., EL HARTI A., MAIMOUNI S., ADIRI Z. 2020. Assessment of the image-based atmospheric correction of multispectral satellite images for geological mapping in arid and semi-arid regions. *Remote Sens Appl Soc Environ* 20, 100420. <https://doi.org/10.1016/j.rsase.2020.100420>
- CHEN C., DENG W., IGNATIEVA M., BI L., DU A., YANG L. 2023. Synergy of urban green space planning and ecosystem services provision: A longitudinal exploration of

- China's development. *Urban Forestry & Urban Greening* 86, 127997. <https://doi.org/10.1016/j.ufug.2023.127997>
- CNN INDONESIA 2023. 16 ribu warga Makassar kesulitan air bersih, status tanggap darurat. (in Indonesian). <https://www.cnn-indonesia.com/nasional/20230909142657-20-996868/16-ribu-warga-makassar-kesulitan-air-bersih-status-tanggap-darurat>
- EFFIONG C., NGANG E., EKOTT I. 2024. Land use planning and climate change adaptation in river-dependent communities in Nigeria. *Environ Dev* 49, 100970. <https://doi.org/10.1016/j.envdev.2024.100970>
- FATIAWAN E., ZUBAIR H., LIAS S.A. 2024. The Impact of Land Use Change on Water Management Conditions of Tallo Watershed [Pengaruh perubahan tata guna lahan terhadap kondisi tata air daerah aliran sungai (DAS) Tallo]. *Jurnal Ecosolum* 13(2): 179–199 (in Indonesian). <https://doi.org/10.20956/ecosolum.v13i2.33319>
- HUANG X., YANG X., WU F., ZHANG J. 2025. Future propagation characteristics of meteorological drought to hydrological drought in the Yellow River basin. *Journal of Hydrology* 649, 132443. <https://doi.org/10.1016/j.jhydrol.2024.132443>
- ILSTEDT U., MALMER A., VERBEETEN E., MURDIARSO D. 2007. The effect of afforestation on water infiltration in the tropics: A systematic review and meta-analysis. *Forest Ecology and Management* 251(1–2): 45–51. <https://doi.org/10.1016/j.foreco.2007.06.014>
- JAYA N.S., PUSPANINGSIH N., PRIHANTO B., PRIYANTO A. 2022. Membumikan teknologi inderaja untuk kehutanan dan lingkungan. IPB Press, Bogor, Indonesia. (in Indonesian).
- KAGABO A.S., SAFARI B., GASORE J., MUTAI B.K., SEBAZIGA J.N. 2024. Assessing the impact of land use land cover changes on land surface temperature over Kigali, Rwanda in the past three decades. *Environmental Sustainability Indicators* 23, 100452. <https://doi.org/10.1016/j.indic.2024.100452>
- LING Z., SHU L., WANG D., LU C., LIU B. 2023. Assessment and projection of the ground-water drought vulnerability under different climate scenarios and land use changes in the Sanjiang Plain, China. *Journal of Hydrology: Regional Studies* 49, 101498. <https://doi.org/10.1016/j.ejrh.2023.101498>
- LIU Y.A., LE M.S., CHIEN H. 2019. Normalized difference latent heat index for remote sensing of land surface energy fluxes. *IEEE Transactions on Geoscience and Remote Sensing* 57(3): 1423–1433. <https://doi.org/10.1109/TGRS.2018.2866555>
- MAHESHWARI B., PINTO U., AKBAR S., FAHEY P. 2020. Is urbanisation also the culprit of climate change? Evidence from Australian cities. *Urban Clim* 31, 100581. <https://doi.org/10.1016/j.uclim.2020.100581>
- MUNA N., PRASETYO Y., SASMITO B. 2020. Analisis perbandingan metode PCA dan indeks mineral lempung untuk pemodelan sebaran kandungan bahan organik tanah menggunakan citra satelit Landsat di Kabupaten Kendal. *Jurnal Geodesi Undip* 9(1): 325–334 (in Indonesian).
- MURRAY V., EBI K.L. 2012. IPCC special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX). *Journal of Epidemiology and Community Health* 66(9): 759–760. <https://doi.org/10.1136/jech-2012-201045>
- NUGROHO S.P., TARIGAN S.D., HIDAYAT Y. 2018. Analysis of Land Use Change and River Discharge in Cicatih Sub Watershed [Analisis perubahan penggunaan lahan dan debit aliran di Sub DAS Cicatih]. *Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan (Journal of Natural Resources and Environmental Management)* 8(2): 258–263 (in Indonesian). <https://doi.org/10.29244/jpsl.8.2.258-263>
- PDASHL 2018. Petunjuk teknis internalisasi rencana pengelolaan daerah aliran sungai ke dalam rencana tata ruang wilayah. Peraturan Direktur Jenderal No. P.8/PDASHL/Set/Kum.1/8/2018. Kementerian Lingkungan Hidup dan Kehutanan, Jakarta. 29 p. (in Indonesian).
- PUTRA E.K., AMARU K., KENDARTO D.R. 2024. Pengaruh perubahan tutupan lahan terhadap respon hidrologi di Sub DAS Cime-ta menggunakan model Soil and Water

- Assessment Tool (SWAT). *Journal Triton* 15(1): 78–92 (in Indonesian). <https://doi.org/10.47687/jt.v15i1.715>
- RAHMAN G., JUNG M.K., KIM T.W., KWON H.H. 2025. Drought impact, vulnerability, risk assessment, management and mitigation under climate change: A comprehensive review. *KSCE Journal of Civil Engineering* 29(1), 100120. <https://doi.org/10.1016/j.kscej.2024.100120>
- SUPRIYANTO J., RAGILIAWAN Z., ROHMAH W. 2023. Pengaruh kebijakan penataan ruang terhadap kualitas hidup masyarakat Kota Surakarta. *Jurnal Bengawan Solo* 2(2): 144–159 (in Indonesian). <https://doi.org/10.58684/jbs.v2i2.61>
- TRAN H.T., CAMPBELL J.B., WYNNE R.H., SHAO Y., PHAN S.V. 2019. Drought and human impacts on land use and land cover change in a Vietnamese coastal area. *Remote Sensing* 11(3), 333. <https://doi.org/10.3390/rs11030333>
- UTAMI N.A., SUJIONO E.H., PALLOAN P. 2020. Analisis tingkat kekeringan meteorologis di wilayah Sulawesi Selatan menggunakan metode indeks presipitasi terstandarisasi (SPI). In: *Proceedings of the National Seminar on Physics (Seminar Nasional Fisika)*, Universitas Negeri Makassar, Makassar, Indonesia: 114–117 (in Indonesian). <https://ojs.unm.ac.id/semnasfisika/article/view/15477/11447>
- VICENTE-SERRANO S.M., BEGUERÍA S., LÓPEZ-MORENO J.I. 2010. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate* 23(7): 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>
- WIJAYANTI D.E., PRIYANTO M.W. 2022. The effect of urbanization on arable land in Indonesia [Pengaruh urbanisasi terhadap lahan garapan di Indonesia]. *Agriscience* 3(1): 230–239 (in Indonesian). <https://doi.org/10.21107/agriscience.v3i1.16679>
- WITTBERG E., TAVARES A.F., SZMIGIEL-RAWSKA K. 2025. Local politics and land take: Using remote sensing data to analyse land-use changes in Sweden. *Journal of Environmental Management* 384, 125387. <https://doi.org/10.1016/j.jenvman.2025.125387>
- XU H., WANG X., ZHAO C., YANG X. 2021. Assessing the response of vegetation photosynthesis to meteorological drought across northern China. *Land Degradation & Development* 32(1): 20–34. <https://doi.org/10.1002/ldr.3701>
- YANG S., YANG X., ZHANG J., GAO X., ZHOU J., WU X. 2024. Assessing the impacts of rural depopulation and urbanization on vegetation cover: Based on land use and nighttime light data in China, 2000–2020. *Ecological Indicators* 159, 111639. <https://doi.org/10.1016/j.ecolind.2024.111639>