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Fenntarthatósághoz kapcsolódó publikációk területi és intézményi mintázatai a magyar felsőoktatásban (2019–2023)

Institutional and Spatial Patterns of Sustainability-Related Publications in Hungarian Higher Education (2019–2023)

ABSZTRAKT

Az ENSZ Fenntartható Fejlődési Céljai (SDG-k) a felsőoktatási intézmények számára egyre fontosabb referenciapontként szolgálnak a nemzetközi láthatóság és a tudományos teljesítmény értékelésében. A tanulmány célja a magyar egyetemek fenntarthatósági kutatási tevékenységének és az SDG-k integrációjának elemzése a 2019 és 2023 közötti időszakban. A kutatás kvantitatív és tematikus megközelítést alkalmaz a Scopus és SciVal adatbázisokból származó publikációs mutatók vizsgálatával, kiemelve az egyetemek között fennálló különbségeket az állami, egyházi és modellváltó intézmények között. Bár a magyar felsőoktatási intézmények jelentős növekedést értek el az SDG-khez kapcsolódó publikációk számában, a kutatási fókusz és a hivatkozási hatás tekintetében markáns eltérések figyelhetők meg. A tanulmány rámutat a rendszerszintű kihívásokra, mint például az erőforrások korlátozottságára és a koherens intézményi stratégiák hiányára, és javaslatokat fogalmaz meg a fenntarthatósági stratégiák erősítésére. Az eredmények hozzájárulhatnak a hazai egyetemi kutatási politika finomhangolásához és a globális SDG-program hatékonyabb megvalósításához.

Kulcsszavak: egyetem, fenntarthatóság, SDG-k

ABSTRACT

The United Nations Sustainable Development Goals (SDGs) have become an increasingly important benchmark for higher education institutions in assessing international visibility and academic performance. This study analyzes the sustainability research activities of Hungarian universities and their integration of the SDGs between 2019 and 2023. Using a quantitative and thematic approach, it examines publication indicators from Scopus and SciVal, highlighting differences among public, church-affiliated, and model-changing universities. Results show a significant increase in SDG-related publications, alongside marked differences in research focus and citation impact. The study identifies systemic challenges—such as resource constraints and incoherent institutional strategies—and offers recommendations to strengthen sustainability strategies. These findings may support the refinement of national university research policies and more effective implementation of the global SDG agenda.

Keywords: university, sustainability, SDGs

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Köszönetnyilvánítás: A TKP2021-NKTA-51 számú projekt a Kulturális és Innovációs Minisztérium Nemzeti Kutatási Fejlesztési és Innovációs Alapból nyújtott támogatásával, a TKP2021-NKTA pályázati program finanszírozásában valósult meg. A tanulmány a Nemzeti Közszolgálati Egyetem Hálózattudományi Kutatóműhely támogatásával készült.

BEVEZETÉS

Az Egyesült Nemzetek Szervezete (ENSZ) 2015-ben elfogadta a Fenntartható Fejlődési Célokat (SDG-k), amelyek 17 átfogó célt és 169 konkrét célkitűzést foglalnak magukban (Melléklet, 1. táblázat). Ezeket a célokat annak érdekében határozták meg, hogy 2030-ra felszámolják a szegénységet, csökkentsék az egyenlőtlenségeket, előmozdítsák a gazdasági növekedést, és védjék a környezetet (ENSZ, 2015). Alapvető fontosságú felismerni a felsőoktatási intézmények szerepét e célok elérésében, mivel oktatási, kutatási és társadalmi szerepvállalásuk közvetlenül hozzájárulhat a fenntarthatósághoz.

A sokszínű intézményi struktúrával rendelkező magyar egyetemek egyedi esettanulmányt kínálnak az SDG-k felsőoktatásban való integrációjának vizsgálatához. Ez az elemzés 18 magyar egyetemre összpontosít, amelyek állami fenntartású, egyházi kötődésű és modellváltó intézmények kategóriába sorolhatók (Melléklet, 2. táblázat). A tanulmány vizsgálja ezeknek az intézményeknek az SDG-kkel kapcsolatos kutatási outputját, tematikus prioritásait.

A kutatás a magyar egyetemek SDG-khez való hozzájárulását értékeli a 2019 és 2023 közötti SDG-fókuszú publikációk trendjeinek elemzésével. Az elemzés középpontjában a tematikus prioritások, valamint az állami, egyházi és modellváltó intézmények hozzájárulása áll, továbbá értékeli ezeknek a publikációknak az idézettségi hatását. A tanulmány azonosítja a rendszerszintű kihívásokat és kiemeli azokat a lehetőségeket, amelyekkel az intézmények publikációs tevékenységei jobban összehangolhatók az SDG-k célkitűzéseivel. A kutatási trendek, tematikus prioritások és intézményi különbségek vizsgálatával a tanulmány célja, hogy információval szolgáltasson a szakpolitikai és gyakorlati döntéshozatal számára, elősegítve a fenntarthatósági stratégiák erősítését és az együttműködés fokozását a magyar egyetemek között a globális SDG-napirend előmozdítása érdekében.

SZAKIRODALMI ELŐZMÉNYEK

A fenntarthatóság témája egyre hangsúlyosabb szerepet kap a köznevelési tantervekben, különösen a földrajz tantárgy keretein belül. Varjas (2021) tanulmánya rámutat arra, hogy a fenntartható fejlődés szempontjai mind Magyarországon, mind Angliában egyre markánsabban jelennek meg a tantervi elvárásokban. Ez az irányvonal a felsőoktatás számára is követendő mintát jelent, hiszen a szemléletformálás már a köznevelésben elkezdődik, és az egyetemeknek kulcsszerepük van a kritikus gondolkodás, valamint a globális felelősségérzet kialakításában.

A fenntarthatóság értékelésének és összehasonlításának egyik fontos eszköze a karbonlábnyom, amely lehetővé teszi a különböző intézmények – így az egyetemek – környezeti hatásainak számszerűsítését. Patocskai (2011) tanulmányában kiemeli, hogy a karbonlábnyom mint mutatószám kiválóan alkalmazható a fenntarthatóság iránti elköteleződés nyomon követésére, legyen szó épületüzemeltetésről, mobilitásról vagy fogyasztási szokásokról. A hazai egyetemek e mutató segítségével nemcsak saját működésük környezeti hatásait csökkenthetik, hanem oktatási és kutatási tevékenységeiken keresztül is hozzájárulhatnak a fenntartható fejlődés céljainak eléréséhez.

A felsőoktatási intézmények szerepe a Fenntartható Fejlődési Célok (SDG-k) elérésében egyre nagyobb elismerést nyer az akadémiai kutatásokban és a szakpolitikai vitákban. Az egyetemek tudásközpontként működnek, amelyek az oktatás, kutatás és közösségi szerepvállalás révén elősegítik a társadalmi átalakulást (Cembranel et al., 2024). A felsőoktatási intézmények (HEI-k) kulcsszerepet játszanak az SDG-orientált kultúra kialakításában azáltal, hogy a fenntarthatóságot beépítik a tantervekbe, kutatási tevékenységekbe és az intézményi irányításba. Az SDG-keretrendszer strukturált támpontot biztosít az egyetemek számára, hogy stratégiai céljaikat globális fenntarthatósági törekvéseikkel összehangolják (Khare & Stewart, 2024).

Világszerte egyre több egyetem igazítja működését és kutatásait az SDG-khez, és olyan értékelési kereteket használ, mint a *Times Higher Education Impact Rankings* és a *QS Sustainability Ranking*, hogy mérjék teljesítményüket a fenntartható fejlődés terén (Szemplér, 2023). A vezető felsőoktatási intézmények kiemelt SDG-tematikákat helyeztek előtérbe, például a minőségi oktatást (SDG 4), az éghajlatvédelmet (SDG 13) és a fenntartható városokat és közösségeket (SDG 11) (Hódiné Hernádi et al., 2023). Ennek eredményeként kialakult az egyetemek „élő laboratóriumként” való felfogása a fenntarthatóság szempontjából, amely hangsúlyozza a fenntarthatósági elvek intézményi irányításba és tantervfejlesztésbe való beépítésének jelentőségét (Purcell et al., 2019).

A fenntarthatóság fogalmát azonban nem szabad egységes, univerzálisan elfogadott elméletként kezelni. Ahogyan Hopwood, Mellor és O'Brien (2005) bemutatja, a fenntarthatósági diskurzusok különböző megközelítéseket ölelnek fel, amelyek gyakran ellentmondásos célokat kódolnak. Ezért az SDG-ket vizsgálva figyelembe kell venni, hogy azok politikai meghatározottságuk miatt nem feltétlenül fedik le a fenntarthatóság tudományos értelmezéseit. Az SDG-k és a fenntarthatósági kutatások témáját több nézőpontból is meg lehet közelíteni:

1. *Aktivizmus és kritikai megközelítések:* Hay (2001) rámutat arra, hogy a felsőoktatási intézményeknek nemcsak publikációs teljesítményük, hanem társadalmi aktív részvételük is fontos a fenntarthatósági kihívások kezelésében.
2. *Rangsorok és intézményi stratégiák:* Hazelkorn (2018) elemzi, hogyan formálják a nemzetközi rangsorok az egyetemek viselkedését, és hogyan befolyásolják ezek az SDG-kutatások prioritásait.
3. *Fenntarthatóság többretegű megközelítése:* Hopwood et al. (2005) bemutatják, hogy a fenntarthatósági diskurzusok különböző paradigmák szerint értelmezhetők, míg Illge és Schwarze (2009) arra hívják fel a figyelmet, hogy az ökológiai és neoklasszikus közgazdasági megközelítések eltérően közelítik meg a fenntarthatóság kérdését.
4. *Tudomány és politika kapcsolata:* Wesselink et al. (2013) szerint a tudományos ismeretek és a szakpolitikai döntéshozatal közötti kapcsolódás kritikus, hiszen az eredmények nem mindig térülnek vissza a társadalmi gyakorlatban.

A közép- és kelet-európai (CEE) régióban, így Magyarországon is, az SDG-k egyetemi stratégiákba való integrációja eltérő mértékben valósul meg, amit az irányítási struktúrák, pénzügyi korlátok és intézményi prioritások alakítanak (Dumitrascu, 2023). Az állami fenntartású, egyházi kötődésű és

modellváltó egyetemek eltérő megközelítést alkalmaznak a fenntarthatóság terén, ami szükségessé teszi az SDG-megvalósításban betöltött szerepük összehasonlító elemzését.

A felsőoktatási intézmények kulcsszerepet játszanak az SDG-k megvalósításában. Ezek az intézmények kutatási, innovációs és szakpolitikai befolyásuk révén segítik a sürgető globális kihívások kezelését. Egyre több egyetem építi be a fenntarthatósági elveket akadémiai küldetésébe, és ösztönzi az interdiszciplináris kutatásokat olyan területeken, mint az éghajlatváltozás, a szegénység csökkentése és a fenntartható gazdasági növekedés (Filho et al., 2025).

Nyugat-Európa, Észak-Amerika és Ázsia egyes részein működő intézmények magasabb szintű SDG-integrációt mutatnak a fejlődő régiókhoz képest. Ez a különbség rámutat arra, hogy az alacsony jövedelmű országokban szükség van méltányos finanszírozási mechanizmusokra és kapacitásépítő kezdeményezésekre a fenntarthatósági törekvések erősítése érdekében (Purcell et al., 2019). Az alábbi területek különösen fontosak az egyetemek SDG-célokhoz való hozzájárulásában:

1. *Kutatás és innováció:* A vezető egyetemek dedikált kutatóközpontokat hoztak létre, amelyek az éghajlatváltozásra, a megújuló energiára és az ökológiai ellenálló képességre összpontosítanak. Például a Cambridge-i Egyetem és a Stanford Egyetem úttörő tanulmányokat végzett a karbon-semlegességről és a fenntartható városfejlesztésről (Khare & Stewart, 2024).
2. *Oktatás és tantervfejlesztés:* Olyan neves egyetemek, mint a Harvard Egyetem és a Sydney-i Egyetem, fenntarthatósági modulokat építettek be különböző tudományágak tanterveibe. Ez biztosítja, hogy minden hallgató találkozzon SDG-kkel kapcsolatos témákkal tanulmányai során (Hong et al., 2022).
3. *Közösségi szerepvállalás és partnerségek:* Számos egyetem működik együtt kormányokkal, civil szervezetekkel és ipari szereplőkkel fenntarthatósági kezdeményezések megvalósításában. Például a Fokvárosi Egyetem (University of Cape Town) fenntartható vízgazdálkodási projekteken dolgozott afrikai közösségekben (Dumitrascu, 2023).

Az SDG-kkel kapcsolatos publikációk megoszlása tematikus egyenlőtlenségeket mutat. Egyrészt az éghajlatváltozáshoz kapcsolódó SDG 13, az oktatáshoz kapcsolódó SDG 4 és az innovációhoz kapcsolódó SDG 9 a kutatási program meghatározó témái. Másrészt bizonyos területek, például az óceánokhoz kapcsolódó SDG 14 és a békéhez kapcsolódó SDG 16, kevesebb figyelmet kapnak (Filho et al., 2025).

Annak ellenére, hogy jelentős előrelépés történt, az egyetemek továbbra is kihívásokkal szembesülnek az SDG-k teljes körű intézményi integrációjában. A pénzügyi korlátozások, bürokratikus akadályok és a fenntarthatósági jelentések egységes keretrendszerének hiánya akadályozza a hatékony végrehajtást (Filho et al., 2025). Továbbá a globális fenntarthatósági rangsorok versenyjellege arra ösztönözheti az intézményeket, hogy bizonyos SDG-ket priorizáljanak, ahelyett, hogy átfogó fenntarthatósági stratégiát alkalmaznának (Purcell et al., 2019).

Az SDG-k eléréséhez a felsőoktatási intézményeknek interdiszciplináris fenntarthatósági kereteket kell alkalmazniuk, amelyek előmozdítják a szakpolitikai érdekképviselést, a technológiai innovációt és a több ágazatot átfogó együttműködéseket. A globális partnerségek erősítése és a méltányos

tudáscsere elősegítése a magas és alacsony jövedelmű országok között kulcsfontosságú lesz ebben a folyamatban.

A magyar egyetemek eltérő mértékben vesznek részt az SDG-k előmozdításában: elsősorban intézményi politikáikon és közösségi programjaikon keresztül. Például a Pécsi Tudományegyetem strukturált fenntarthatósági programokat dolgozott ki, és részt vett az UI GreenMetric World University Ranking értékelésében, amely kiemeli környezettudatos elköteleződését (Orbán et al., 2021). Hasonlóképpen, a Szegedi Tudományegyetem szerepelt a QS Sustainability Ranking-ban, elismerve hozzájárulását a minőségi oktatáshoz és a társadalmi egyenlőséghez (Szegedi Tudományegyetem ETSZK, 2022).

A Fenntarthatósági Mutatók Kutatóközpont a Budapesti Corvinus Egyetemen átfogó tanulmányokat végzett az ökológiai lábnyom és a fenntarthatósági értékelési keretrendszerek témájában (Csutora & Zsóka, 2023). Emellett a Széchenyi István Egyetem kiemelkedő elkötelezettséget mutat a fenntarthatósági célokat támogató technológiai innovációk iránt (Fenntarthatóság SZE, 2023). A magyar egyetemek SDG-k iránti elköteleződése intézményi kereteiktől függően eltérő módon valósul meg:

1. *Állami fenntartású egyetemek:* Ezek az intézmények törekednek az SDG-elvek beépítésére akadémiai kutatásaikba és interdiszciplináris programjaikba. Gyakran használnak fel európai uniós és hazai forrásokat fenntarthatósági projektek finanszírozására (Szemlér, 2023). Például a Budapesti Műszaki és Gazdaságtudományi Egyetem kiváló példája annak, hogyan lehet a köz- és magánszektor prioritásait hatékonyan ötvözni. Az egyetem alkalmazott kutatásban és innovációban elért eredményei jelentős mértékben hozzájárulnak az SDG 9 célkitűzéseéhez.
2. *Egyházi fenntartású egyetemek:* Az egyházi intézmények az etikus vezetés, a társadalmi igazságosság és a közösségi fenntarthatósági kezdeményezések kiemelt támogatására összpontosítanak, amelyek összhangban állnak az inkluzivitásra és társadalmi felelősségvállalásra irányuló SDG-célokkal (Khare & Stewart, 2024). Például a Pázmány Péter Katolikus Egyetem Roma Kollégiuma olyan kezdeményezés, amely mentori programokkal, képzésekkel és közösségépítéssel támogatja a roma fiatalokat, ezáltal hozzájárul az egyenlő oktatási lehetőségek biztosításához és a társadalmi egyenlőtlenségek csökkentéséhez. Ez a program kapcsolódik az SDG 4 és az SDG 10 célkitűzésekhez is.
3. *Modellváltó egyetemek:* Az irányítási és finanszírozási reformok révén létrejött intézmények hibrid modellt alkalmaznak, ahol megtaláljuk az akadémiai kutatást és a magánszektorbeli szervezetekkel történő gyakorlati együttműködéseket is. (Ezek az intézmények a vizsgált időszakban fokozatosan alakultak át állami fenntartású egyetemből modellváltóvá.) Azonban ezek az intézmények kihívásokkal szembesülnek a fenntarthatósági irányítási keretek hatékony megvalósításában (Gechev, 2008). Az SDG-khez való hozzájárulásuk egyenlőtlenségeket mutat, mivel a köz- és magánszektor eltérő prioritásai között kell egyensúlyozniuk. Kiemelkedő példa a Szegedi Tudományegyetem, amely SDG 3 célkitűzéséhez járul hozzá biomedikai kutatásaival.

A fenntarthatóság iránti elkötelezettség erősítése érdekében 2022 szeptemberében megalakult a *Magyar Egyetemek Fenntarthatósági Platformja (MEFP)*, amelyhez 14 magyar egyetem – állami, egyházi és modellváltó intézmények egyaránt – csatlakozott. A platform célja kettős: egyrészt a fenntarthatósági legjobb gyakorlatok és tapasztalatok megosztása, másrészt olyan együttműködési kezdeményezések koordinálása, amelyek a fenntarthatósági célok megvalósítását szolgálják (Univ Pécs, 2025).

Az adatok elemzése azt mutatja, hogy a magyar egyetemek különös hangsúlyt fektetnek bizonyos SDG-kre, nevezetesen: SDG 3, SDG 4, SDG 13 és SDG 11. Az SDG 3 témájú publikációk az egészségügyhöz kapcsolódó kutatások globális jelentőségét tükrözi. Az SDG 4 hangsúlyozása az inkluzív, méltányos oktatás és az egész életen át tartó tanulás lehetőségeinek intézményközi előmozdításában nyilvánul meg. Az SDG 13 hangsúlyozása nyilvánvaló a megújuló energiával, az éghajlatváltozáshoz való alkalmazkodással és a fenntarthatósági oktatással kapcsolatos kutatásokban. Végül az SDG 11 hangsúlyozása a városfejlesztéssel, a fenntartható mobilitással és a lakhatási megoldásokkal kapcsolatos tanulmányokban nyilvánul meg (Náhlík et al., 2024).

Azonban számos rendszerszintű kihívás akadályozza a fenntartható fejlődési célok integrációjának hatékonyságát. E kihívások közül az első az erőforrások szűkössége, amelyek korlátozzák mind a kutatás minőségét, mind pedig a kutatás hatókörét. A második a koordinációs hiányosságok, amelyek az intézmények közötti koherens stratégiák hiánya miatt töredezett erőfeszítéseket eredményeznek. A harmadik a láthatóság és a jelentéstétel, amely akadályozza a nemzetközi elismerést az ellentmondásos mérési és jelentéstételi mechanizmusok miatt (Hong et al., 2022).

A fenntartható fejlődési célokkal kapcsolatos kutatások bizonyítottan növelik az egyetemek globális láthatóságát, ezáltal javítják a rangsorolásuk teljesítményét (Filho et al., 2025). Mindazonáltal a kutatások általános hatása az SDG-k előrehaladására Magyarországon szerény a Nyugat-Európában megfigyeltekhez képest, ami rávilágít mind az intézményi támogatás, mind a társadalmi szerepvállalás terén tapasztalható különbségekre (Smolennikov et al., 2024).

Jelentős eltérés figyelhető meg a nyugat-európai egyetemek és magyar társaik SDG-kkel kapcsolatos elkötelezettsége között. A nyugat-európai intézmények erősebb finanszírozással, interdiszciplináris programokkal és jól megalapozott fenntarthatósági kultúrával rendelkeznek (Smolennikov et al., 2024). Magyarország a CEE régió többi országához képest viszonylag erős SDG-elköteleződést mutat, azonban jelentős regionális különbségek figyelhetők meg a szakpolitikai keretek és az intézményi támogatás tekintetében (Szemplér, 2023).

Összefoglalva, létfontosságú elismerni az egyetemek kulcsfontosságú szerepét az ENSZ fenntartható fejlődési céljainak (SDG-k) hazai és nemzetközi szintű előmozdításában. A magyar felsőoktatási intézmények a kutatás, az oktatás és a közösségi szerepvállalási kezdeményezések révén egyre növekvő mértékben járulnak ezen célokhoz. Ugyanakkor akadályokba ütköznek stratégiáiknak a globális legjobb gyakorlatokkal való összehangolásában. Globális szinten a fejlett régiók egyetemei magasabb szintű elkötelezettséget mutatnak, ami rávilágít arra, hogy a felsőoktatásban a fenntarthatósági kihívások kezeléséhez fokozott finanszírozási mechanizmusokra és együttműködési keretekre van szükség.

MÓDSZEREK

A kutatás vegyes módszertani megközelítést alkalmaz, amely a kvantitatív tudományometriai elemzést kiegészíti a módszertani reflexióval. A vizsgálat alapját a Scopus és SciVal adatbázis szolgáltatja, amelyek lehetővé teszik a fenntarthatósági célokhoz (SDG-k) kapcsolódó tudományos közlemények számának, arányának és hivatkozási hatásának elemzését.

Az elemzés középpontjában a magyar felsőoktatási intézmények 2019 és 2023 közötti teljesítménye áll. A vizsgált 18 egyetem három csoportba sorolható: állami, egyházi és modellváltó intézmények. A kutatás célja ezek komparatív összehasonlítása az SDG-fókuszú tudományos teljesítményük alapján.

Fontos hangsúlyozni, hogy a kvantitatív megközelítés nem tekinthető objektívnek a szó klasszikus értelmében, hiszen számos módszertani döntés befolyásolja az eredményeket: ilyen az alkalmazott adatbázis kiválasztása, az SDG-besorolás logikája, valamint az elemzésbe vont mutatók és csoportosítási szempontok. Az SDG-besorolások a Scopus saját, algoritmikus, kulcsszavakra és szövegelemzésre épülő rendszere alapján történnek, amelyek részletes leírását az Elsevier nyilvánosan elérhető dokumentációi tartalmazzák. (Bedard-Vallee et al., 2023)

A Scopus 16 SDG-t kezel külön kategóriaként; az SDG 17 nem jelenik meg strukturált formában, így a kutatás ezt nem tudta külön vizsgálni. A besorolás nem tudományterületi vagy szerzői önjelölésen, hanem tartalmi NLP-alapú szűrőkön alapul, ezért bizonyos tudományterületek – elsősorban az orvostudomány – felülreprezentálódnak (pl. SDG 3 „Good Health and Well-being”), míg más témák (pl. SDG 16, SDG 10) alulreprezentáltak lehetnek. Ezt a torzítást tudatosan figyelembe vettük az elemzés értelmezése során.

A kvantitatív adatokon túl a kutatás kísérletet tesz a tematikai és intézményi profilok feltérképezésére is, azaz annak vizsgálatára, hogy az SDG-hez rendelt publikációk mennyiben tükröznék tudatos kutatói fókuszot, és mennyiben az intézményi szakprofil „automatikus” lenyomatát. A módszertani megközelítés tehát kettős célt szolgál: egyrészt adatalapú összehasonlítást biztosít, másrészt teret ad a módszertani torzulások kritikus értelmezésének.

A kutatás célja a fenntarthatósággal (SDG-kkel) kapcsolatos publikációs tevékenység vizsgálata a magyar egyetemek körében, különös tekintettel annak mennyiségi trendjeire, tematikai összetételére és hivatkozási hatására a 2019 és 2023 közötti időszakban. A tanulmány elsőként azt vizsgálja (K1a), hogyan változott az SDG-hez kapcsolódó közlemények száma az egyes felsőoktatási intézményekben, majd arra keresi a választ (K1b), hogy mely egyetemek mutattak kiemelkedő növekedést ezen a területen, és hogy ez a növekedés milyen tényezőkre – például az intézményi kutatási profilra vagy tudományterületi sajátosságokra – vezethető vissza.

A publikációs tevékenység tematikai szerkezetének feltérképezésével a kutatás bemutatja (K2a), hogy a magyar egyetemek milyen mértékben járulnak hozzá az egyes SDG-célokhoz, illetve melyek azok a tematikus területek, amelyek dominálnak. Ezen felül megvizsgáljuk (K2b), hogy az egyes SDG-khez tartozó publikációk megoszlása hogyan kapcsolódik az intézmények szakmai profiljához és stratégiai fókuszaihoz.

A tanulmány kiemelt figyelmet fordít arra is, hogy az SDG-releváns publikációk milyen idézettséget érnek el az egyes intézményeknél (K3a), és hogy mely tényezők befolyásolják ezeknek a közleményeknek a tudományos hatását. Elemzi azokat a kihívásokat (K3b), amelyekkel az alacsonyabb láthatóságú intézmények szembesülnek az SDG-kutatások területén, valamint azokat a stratégiákat, amelyek segíthetik a publikációs láthatóság növelését. Végül a kutatás arra is választ keres (K3c), hogy az intézményi kutatási prioritások és profilok milyen mértékben tükröződnek vissza az SDG-ekkel kapcsolatos publikációk idézettségi mutatóiban.

EREDMÉNYEK

A fenntarthatósághoz kapcsolódó publikációk strukturális és időbeni jellegzetességei

Az alapvető statisztikai elemzés számos figyelemre méltó eredményt hozott az egyetemek publikációs tevékenységével kapcsolatban. A vizsgált időszakban átlagosan egy egyetem 3865 cikket publikált, melyek közül 1279 kapcsolódott az SDG 1–16 célokhoz, ami azt jelenti, hogy az SDG 1–16 témákkal összefüggő publikációk az összes közlemény mintegy 33,3%-át tették ki. Az egyetemek között azonban jelentős eltérések figyelhetők meg: a publikációk teljes számának szórása 3575, míg az SDG 1–16-hoz kapcsolódó publikációk esetében ez az érték 1203, ami az intézmények közötti publikációs teljesítmény tekintetében jelentős különbségekre utal.

A minimális és maximális értékek tovább szemléltetik ezeket az eltéréseket: a legkevesebb publikációt megjelentető egyetem 396 cikket adott ki, míg a legtöbbet publikáló intézmény 11227 cikket. Az SDG 1–16-hoz kapcsolódó publikációk száma 84 és 4268 között mozog, ami hasonló mértékű eltéréseket mutat. Arányok tekintetében az SDG 1–16 publikációk az összes publikáció 18,8%-ától 49,7%-áig terjedtek, arra utalva, hogy míg egyes egyetemek jelentős hangsúlyt fektetnek ezekre a témákra, mások kevésbé tartják ezeket prioritásnak. Az elemzés tehát átfogó képet adott az egyetemek publikációs aktivitásáról és annak SDG 1–16 célokkal való összefüggéséről (1. ábra).

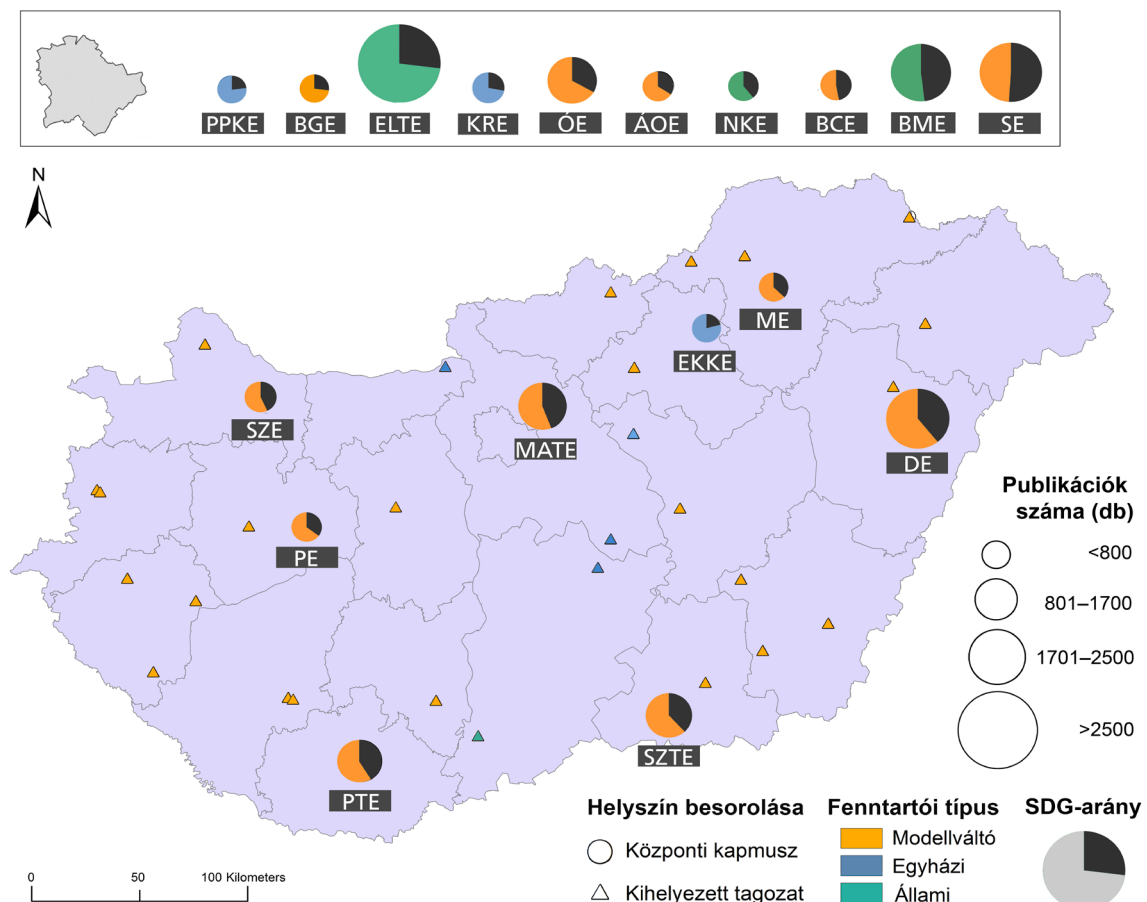
Az Eötvös Loránd Tudományegyetem rendelkezik a legmagasabb publikációs számmal (1–2 ábra). Számos kisebb egyetem jelentősen kevesebb publikációt mutatott fel, ami nemcsak a kutatási aktivitás szintjében, hanem az intézményi méretben, illetve az oktatói létszámokban is tapasztalható jelentős eltéréseket is kiemeli az intézmények között. A jelen kutatás fókusza az egyetemek SDG 1–16 célokhoz kapcsolódó publikációinak számán van (Melléklet, 3. táblázat). A Semmelweis Egyetem vezet abszolút értékben. Ugyanakkor az arányok részletesebb vizsgálata – ahogy az ábra is mutatja – azt is jelzi, hogy nem minden egyetem fordít egyenlő figyelmet az SDG 1–16 témákra.

Az SDG 1–16-hoz kapcsolódó publikációk aránya az összes publikáció számához viszonyítva százalékos formában került bemutatásra (1. ábra). Ez az elemzés azt mutatja, hogy bizonyos egyetemek, amelyeknek összességében kevesebb publikációjuk van, például a Budapesti Gazdasági Egyetem, nagyobb arányban fordítanak figyelmet ezekre a célokra. Ezzel szemben nagyobb intézmények, mint

például az Eötvös Loránd Tudományegyetem, arányosan kevesebb figyelmet szentelnek az SDG 1–16-hoz kapcsolódó publikációknak. Ezek a megfigyelések eltérő kutatási prioritásokat jeleznek az akadémiai intézményekben.

1. ábra: Az SDG 1–16-hoz kapcsolódó publikációk aránya a vizsgált egyetemeken 2023-ban

Figure 1. Share of publications related to SDGs 1–16 at the universities under study in 2023



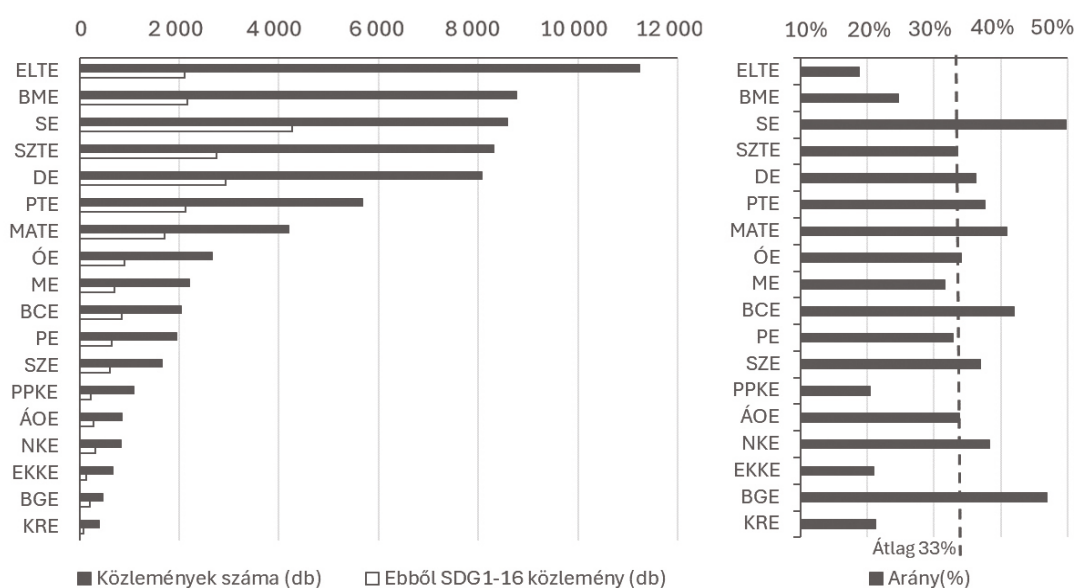
A trendanalízis jelentős eltéréseket mutat az egyetemek összes publikációjának növekedési mintázatában 2019 és 2023 között. A Budapesti Műszaki és Gazdaságtudományi Egyetem folyamatosan vezet az összes kutatási output tekintetében, ami erős kutatási kapacitását tükrözi. Ezzel szemben kisebb intézmények, mint például az Állatorvostudományi Egyetem és a Budapesti Gazdasági Egyetem, mérsékelt növekedést mutatnak, ami kutatási tevékenységük fokozatos fejlődését jelzi.

Az SDG-kkel kapcsolatos publikációk számát illetően jelentős eltérések tapasztalhatók az egyetemek között. Egyes intézmények, például a Budapesti Corvinus Egyetem, konzisztens és fokozatos növekedést mutatnak az idő előrehaladtával. Más intézmények, mint például a Budapesti Gazdasági Egyetem, kezdetben mérsékelt ütemben fejlődnek, majd később felgyorsítják az SDG-kel kapcsolatos publikációkra irányuló figyelmüket. Az SDG-publikációk aránya az összes kutatási outputhoz viszonyítva intézményenként eltérően alakul. Fontos megjegyezni, hogy a Budapesti Gazdasági Egyetem következetesen magas arányban publikál SDG-kkel kapcsolatos kutatásokat, kiemelve

elkötelezettségét a fenntarthatóság iránt. A legtöbb egyetem esetében egyértelmű növekedési tendencia figyelhető meg mind az összes publikáció, mind az SDG-publikációk terén, azonban a növekedés üteme intézményenként jelentős eltéréseket mutat. Az olyan egyetemek, mint a Budapesti Gazdasági Egyetem és a Budapesti Corvinus Egyetem, kiemelten foglalkoznak SDG-kel kapcsolatos kutatásokkal, amit jelentős és növekvő hozzájárulásukat igazolja ezen a területen.

2. ábra: Az egyes egyetemek összes publikációjának száma, az SDG 1–16-hoz kapcsolódó publikációk száma, valamint az SDG 1–16-hoz kapcsolódó publikációk aránya 2019 és 2023 között.

Figure 2. The total number of publications across universities, the number of publications related to SDGs 1–16 by each university, and the proportion of publications related to SDGs 1–16 between 2019 and 2023.



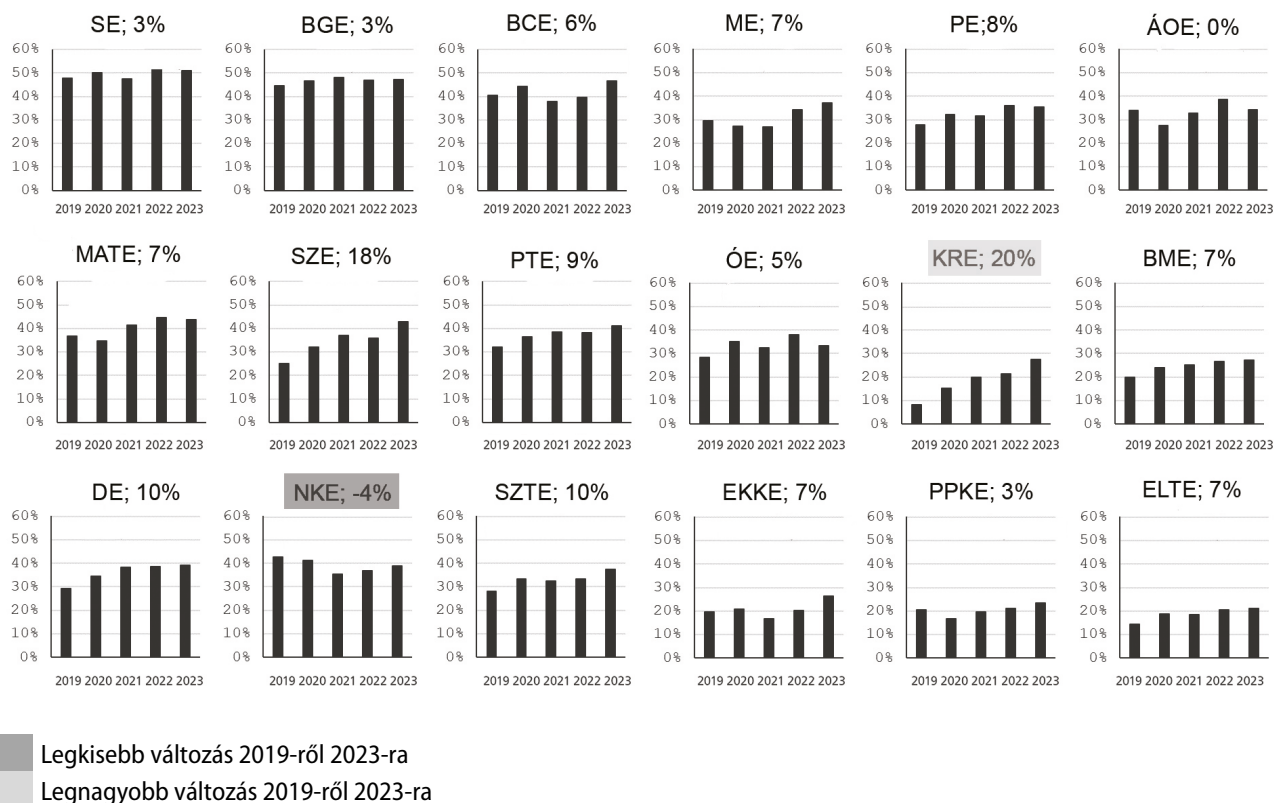
Mindazonáltal továbbra is van lehetőség a fejlődésre. Például a magas publikációs teljesítménnyel rendelkező intézmények, mint a Budapesti Műszaki és Gazdaságtudományi Egyetem, tovább növelhetnék fenntarthatósági elkötelezettségüket azáltal, hogy az SDG-kel kapcsolatos publikációk arányát fokozzák teljes kutatási outputjukon belül. Ugyanakkor az alacsonyabb publikációs teljesítményt mutató intézmények, mint például a Károli Gáspár Református Egyetem, interdiszciplináris megközelítések alkalmazásával, nemzetközi együttműködéseik bővítésével erősíthetik pozíciójukat e téren. Figyelemre méltó, hogy a vizsgált időszakban a legnagyobb, 20%-os növekedés, a Károli Gáspár Református Egyetemen volt megfigyelhető, míg ezzel szemben a Nemzeti Közszolgálati Egyetem 4%-os csökkenést mutatott (3. ábra).

Az adatok összesítése alapján a legnépszerűbb kutatási terület az SDG 3 (*jó egészség*), amelyhez összesen 11656 publikáció kapcsolódik. Második helyen áll az SDG 9 (*innováció és jó infrastruktúra*) 2273 publikációval. Ezen kívül az SDG 7, 8, valamint a 13 (*újrahasznosítható és megfizethető energia; jó munkalehetőségek és gazdaságok; éghajlatváltozás elleni fellépés*) szintén kiemelt figyelmet kaptak; ezek mindegyike meghaladja az 1000 publikációt. Ezzel szemben az SDG 1 (*szegénység*

felszámolása) és SDG 5 (*nemek közötti egyenlőség*) a legkevésbé kutatott területek közé tartoznak, ezekben a témákban kevesebb mint 400 publikáció született (Melléklet, 4. táblázat).

3. ábra: Az SDG 1–16-hoz kapcsolódó publikációk arányának alakulása az egyetemeken 2019 és 2023 között.

Figure 3. Trends in the proportion of publications related to SDGs 1–16 across universities between 2019 and 2023.



Egyetemi szinten az SDG 3 kutatási területét a Semmelweis Egyetem vezeti, összesen 4000 publikációval, amely tükrözi az intézmény egészségügyi profilját. A Debreceni Egyetem szintén jelentős eredményeket ért el ezen a területen 1756 publikációval, valamint kimagasló kutatásokat végzett az SDG 13 és 15 területén (*éghajlatváltozás elleni fellépés; fenntartható földhasználat*). Az SDG 7 és SDG 9 kutatása különösen erős a Budapesti Műszaki és Gazdaságtudományi Egyetemen, amely összhangban áll az intézmény mérnöki és műszaki tudományos profiljával.

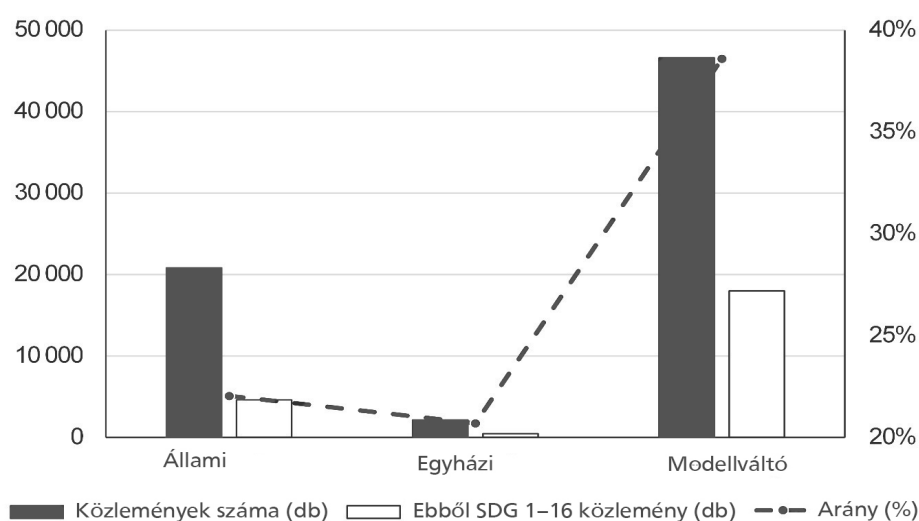
Az Eötvös Loránd Tudományegyetem sokszínű kutatási portfólióval rendelkezik, kiemelkedő teljesítményt nyújtva az SDG 3, 12 és 16 területén (*jó egészség; a források felelősségteljes használata; béke és igazság*). A Magyar Agrár- és Élettudományi Egyetem jelentős publikációs aktivitást mutat az SDG 2 (*éhezés megszüntetése*) és az SDG 15 (*fenntartható földhasználat*) területén, amely összhangban van az intézmény agrártudományi profiljával.

Érdekes megfigyelni, hogy a kisebb egyetemek, például az Eszterházy Károly Katolikus Egyetem és a Károli Gáspár Református Egyetem, kevesebb SDG-hez kapcsolódó publikációt közöltek. Azonban ezek közül az Eszterházy Károly Katolikus Egyetem aktivitást mutatott az SDG 13 (*éghajlatváltozás*) területén. Ezzel szemben a Nemzeti Közszolgálati Egyetem kiemelkedő eredményeket ért el az SDG 16 témakörében, ami összhangban van az intézmény társadalmi és kormányzati fókuszával.

2019 és 2023 között jelentős növekedés történt mind az összes publikációk számában, mind az SDG 1–16-tal foglalkozó publikációk arányában különböző egyetemi típusok között. Az adatok markáns trendeket jeleznek a publikációs aktivitásban, valamint a fenntarthatósági kutatások növekvő jelentőségét (4. ábra).

4. ábra: Az összes publikáció és az SDG 1–16-hoz kapcsolódó publikációk száma, valamint az SDG-vel kapcsolatos publikációk aránya 2019 és 2023 között az egyetemtípusok szerint.

Figure 4. The total number of publications, the number of publications related to SDGs 1–16, and the proportion of SDG-related publications between 2019 and 2023 based on the type of university.



A modellváltó egyetemek mutatták a legjelentősebb fejlődést, 2019 és 2023 között a publikációik száma 7335-ről 10811-re emelkedett, ami közel 47%-os növekedést jelent. Az állami egyetemek szintén növekedést mutattak, publikációik száma 3820-ról (2019) 4491-re (2023) emelkedett, ami körülbelül 17%-os növekedést jelent. Hasonló tendencia figyelhető meg az egyházi fenntartású egyetemekenél, ahol a publikációk száma 312-ről (2019) 537-re (2023) nőtt, ami 72%-os növekedést jelent. Az összes egyetemtípus összesített publikációinak száma 2019-ben 11467 volt, amely 2023-ra 15839-re emelkedett, ami 38%-os növekedést mutat.

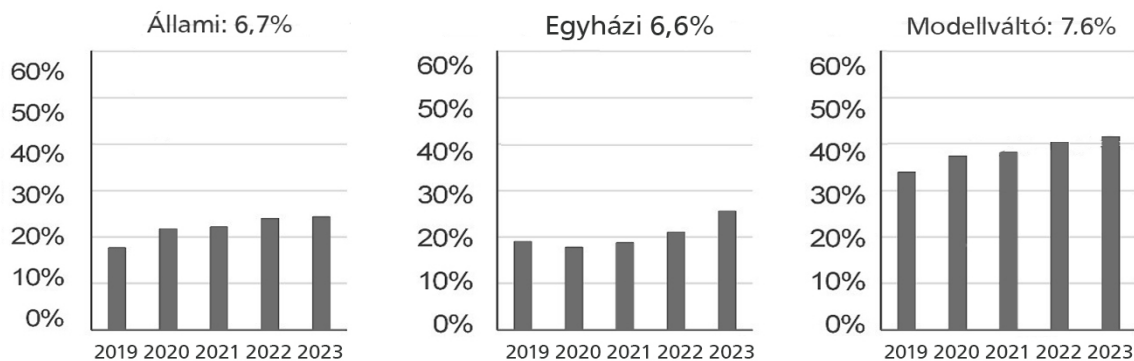
Az SDG 1–16-hoz kapcsolódó publikációk aránya szintén növekvő tendenciát mutatott. Az állami egyetemeken az arány 17,6%-ról (2019) 24,3%-ra (2023) nőtt. Az egyházi egyetemeken hasonló növekedés figyelhető meg, az arány 18,9%-ról (2019) 25,5%-ra (2023) emelkedett. A modellváltó egyetemekenél már kezdetben magasabb volt az SDG 1–16-tal kapcsolatos publikációk aránya (33,9% 2019-ben), amely 2023-ra 41,5%-ra növekedett. Az SDG 1–16-hoz kapcsolódó publikációk aránya összességében 28%-ról (2019) 36%-ra (2023) nőtt, ami egyértelmű elmozdulást jelez a fenntarthatóságra összpontosító kutatások felé (5. ábra).

Ez az elemzés több kulcsfontosságú trendet tár fel. Az összes publikáció és az SDG 1–16-hoz kapcsolódó kutatások növekedése hangsúlyozza az egyetemek növekvő teljesítményét és szerepét a globális kihívások kezelésében. Az egyetemtípusok közötti különbségek azt mutatják, hogy a modellváltó egyetemek vezetnek a publikációs teljesítmény és a fenntarthatóságra való fókuszban. Az állami egyetemek stabil növekedést mutattak, az egyházi egyetemek kisebb, de figyelemre méltó

előrelépést értek el. Az SDG 1–16-tal kapcsolatos publikációk növekvő aránya minden egyetemtípus esetében rávilágít az akadémiai szektor egyre nagyobb elköteleződésére a fenntarthatósági célok iránt.

5. ábra: Az SDG 1–16-hoz kapcsolódó publikációk arányának alakulása 2019 és 2023 között egyetemtípusok szerint.

Figure 5. Trends in the proportion of publications related to SDGs 1–16 between 2019 and 2023 based on the type of university.



Összességében az adatok következetes és jelentős növekedést mutatnak a fenntarthatósági kutatások és az általános publikációs aktivitás terén. Egyértelmű, hogy az egyetemek kulcsszerepet játszanak a globális fenntarthatósági program előmozdításában, azonban minden egyetemtípus profiljával összhangban, egyedi módon járul hozzá ehhez a fejlődéshez.

Az SDG-k szempontjából vizsgált, 2019 és 2023 közötti időszakra vonatkozó magyar egyetemi publikációk hivatkozási teljesítményének elemzése során az adatok jelentős eltéréseket mutatnak mind az egy publikációra eső átlagos hivatkozásszám, mind az egyes SDG-területek között. Átlagosan a magyar egyetemek 12,7 hivatkozást értek el publikációként az SDG-kkel kapcsolatos kutatások esetében. Azonban az intézmények között, valamint az egyes SDG-célok között is jelentős különbségek figyelhetők meg (5. ábra).

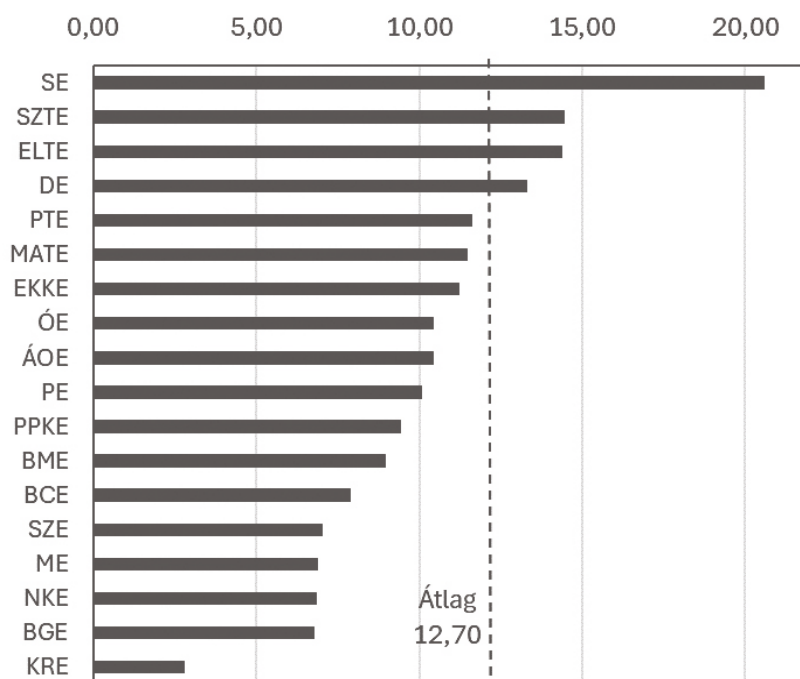
A Semmelweis Egyetem érte el a legmagasabb átlagos idézettségi arányt az összes vizsgált egyetem közül, 20,56 idézet/publikáció értékkel. Kiemelkedően teljesített az SDG 3 területén, ahol 29,32 idézet/publikáció értéket ért el, ami rávilágít az egészségtudományi kutatások globális jelentőségére. Ezen túlmenően a Semmelweis Egyetem kiváló eredményeket mutatott a fenntartható városfejlesztés területén SDG 11, ahol 73,18 idézet/publikáció értéket produkált, ez a legmagasabb érték az egész adatbázisban a magyar egyetemek vonatkozásában. A Debreceni Egyetem szintén erős eredményeket ért el, különösen az SDG 2 és SDG 3 területén, ahol 16,83, illetve 18,67 idézet/publikáció értékeket regisztráltak. Ezek az adatok az agrár- és élettudományi kutatások fontosságát hangsúlyozzák az egyetem kutatási profiljában.

Az Eötvös Loránd Tudományegyetem kiegyensúlyozott teljesítményt mutatott, különösen magas idézettségi értékeket elérve több SDG-célterületen: SDG 3: 16,63 idézet/publikáció, SDG 13: 18,41 idézet/publikáció, SDG 15: 11,54 idézet/publikáció. Ezzel szemben a Pannon Egyetem kimagasló eredményeket ért el az SDG 5 területén, ahol 50 idézet/publikáció arányt mutatott, amely az összes

SDG-kategória legmagasabb értéke. Ez az intézmény célzott kutatási tevékenységét tükrözi ezen a területen, amely jelentős nemzetközi elismerést váltott ki.

6. ábra: Az SDG 1–16-hoz kapcsolódó publikációk idézettségi mutatói az egyetemeken 2019 és 2023 között.

Figure 6. Trends in the number of citations to publications related to SDGs 1–16 across universities between 2019 and 2023.



A kisebb intézmények közül az Óbudai Egyetem kiemelkedő teljesítményt nyújtott az SDG 12 és az SDG 15 területén, ahol idézettségi arányai 22,15 és 31,59 idézet/publikáció voltak. Ezzel szemben a Károli Gáspár Református Egyetem és az Eszterházy Károly Katolikus Egyetem alacsonyabb átlagos idézettségi arányokat mutattak, ami alacsonyabb kutatási aktivitásra vagy kisebb nemzetközi jelenletre utalhat.

Az SDG-kel kapcsolatos publikációk idézettsége tekintetében az általános trendek elemzése azt mutatja, hogy az SDG 3 következetesen kiváló idézettségi mutatókat produkál, ami az egészségügyi kutatások globális jelentőségét hangsúlyozza. Hasonlóan kiemelkedő idézettségi értékek figyelhetők meg az SDG 6 és SDG 13 (*tiszta víz és köztisztaság; éghajlatváltozás elleni fellépés*) esetében is, ami a környezetvédelmi kutatások növekvő fontosságát jelzi. Ezzel szemben az SDG 4 és SDG 5 (*minőségi oktatás; nemek közötti egyenlőség*) viszonylag alacsony idézettséget mutat számos intézmény esetében, ami az egyetemi kutatási prioritások és az erőforrások elosztásának eltéréseire utalhat (Melléklet, 5. táblázat).

Összességében az adatok egyértelmű eltéréseket mutatnak az egyetemek kutatási fókuszja és az SDG-különböző céljaihoz való hozzájárulása terén. A nagyobb egyetemek, például a Semmelweis Egyetem, a Debreceni Egyetem és az Eötvös Loránd Tudományegyetem, kiemelkedő nemzetközi idézettségi teljesítményt értek el egyes területeken. Más egyetemek szűkebb fókuszú, de célzott kutatásokat végeztek, amelyek meghatározott SDG-körökre koncentrálnak. Az is előfordulhat, hogy

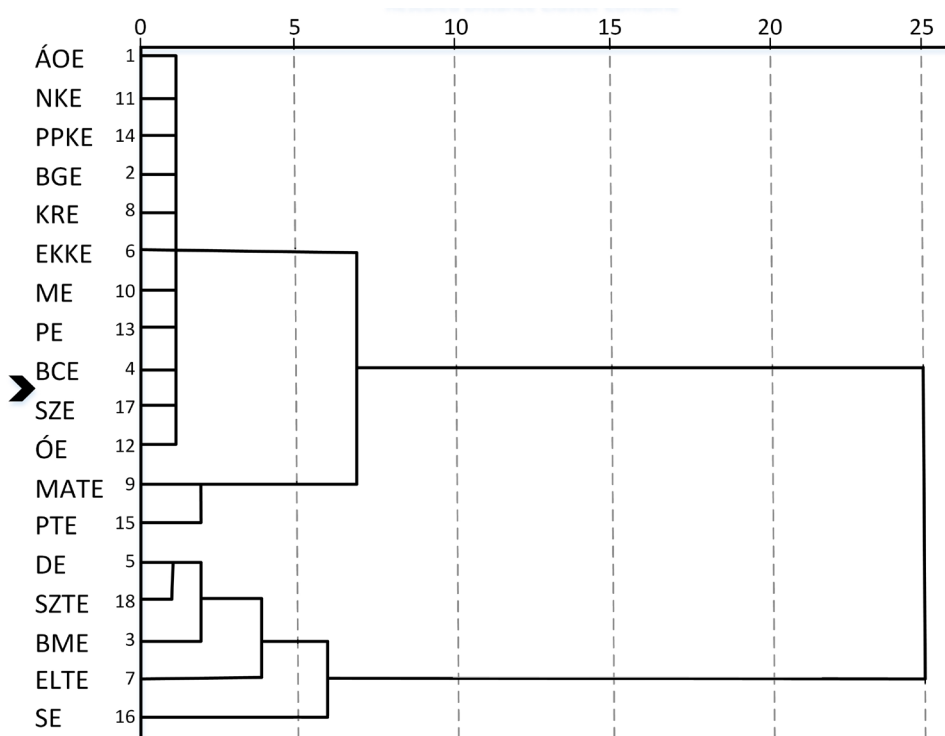
ezek olyan területek, amit vagy nagyon lefednek a nagy nyugat-európai egyetemek, vagy olyanok, melyeken a nemzetközi cikkek is viszonylag alacsonyabb hivatkozási számokat érnek el. Ezért az alacsonyabb idézettségi arányokkal rendelkező SDG-kel kapcsolatos publikációk fejlesztése, továbbá a jelentősebb egyetemekkel való partnerségek kialakítása hozzájárulhat a magyar felsőoktatási intézmények SDG-kutatási hatásának felerősítéséhez, valamint a fenntarthatósági célok szélesebb körű előrehaladásához, illetve javíthatná a magyar egyetemek nemzetközi láthatóságát.

A kutatási aktivitás koncentráltsága – klaszterek és stratégiák

A dendrogram-elemzés, amely az egyetemi publikációk hierarchikus klaszterelemzését és az SDG 1–16-hoz kapcsolódó cikkek arányát vizsgálja, három fő klasztert azonosított az egyetemek kutatási teljesítménye és SDG-kel kapcsolatos publikációkhoz való igazodása alapján (7. ábra). A klaszterek meghatározásánál a publikációk SDG-k szerinti eloszlását, idézettségi mutatókat és nemzetközi együttműködéseket vettük figyelembe. Az elemzés részletesebb magyarázatot kapott az egyes intézmények fenntarthatósági stratégiáinak figyelembevételével.

7. ábra: A magyar egyetemek publikációinak dendrogramja és az SDG 1–16-hoz kapcsolódó cikkek aránya.*

Figure 7. The dendrogram of publications by universities and the proportion of articles related to SDGs 1–16.**



* Függőleges tengely: egyetemek sorszáma az elemzési adatbázisban. Vízszintes tengely: újraméretezett távolságok, normalizált skálán jelezve, hogy az egyes klaszterek mekkora relatív távolságban kerültek összevonásra.

** Vertical axis: university index in the analytical database. Horizontal axis: rescaled distances on a normalized scale, indicating the relative distance at which clusters were merged.

Az *első klaszter* az alacsony publikációs teljesítménnyel rendelkező intézményeket foglalja magában, amelyek viszonylag kisebb hangsúlyt fektetnek a fenntarthatóságra. Ebbe a csoportba tartozik az Állatorvostudományi Egyetem, a Nemzeti Közszerológati Egyetem és a Pázmány Péter Katolikus Egyetem. Ezek az intézmények alacsony kutatási aktivitást mutatnak, és kisebb mértékben járulnak hozzá az SDG-célokhoz.

A *második klaszter* a közepes publikációs teljesítményt mutató egyetemeket jelenti, amelyek kutatásai mérsékelten igazodnak a fenntarthatósági célokhoz. Ebbe a csoportba tartozik a Magyar Agrár- és Élettudományi Egyetem és a Pécsi Tudományegyetem. Ezek az egyetemek sokszínű kutatási portfólióval rendelkeznek, de nem mutatnak kiemelkedő dominanciát egyetlen SDG-területen sem.

A *harmadik klaszter* azokat az intézményeket tartalmazza, amelyek magas publikációs teljesítményt és erős SDG-orientált kutatási tevékenységet mutatnak. A Semmelweis Egyetem kiemelkedő teljesítményt mutat az SDG 3 területén, amely összhangban áll egészségügyi fókuszával. A Budapesti Műszaki és Gazdaságtudományi Egyetem és az Eötvös Loránd Tudományegyetem szoros kapcsolatban áll ebben a klaszterben, mivel mindkettőt magas publikációs teljesítmény jellemzi, és kutatásaikat számos SDG-célterületre kiterjesztik. A Szegedi Tudományegyetem és a Debreceni Egyetem szintén ebbe a csoportba tartozik, mivel jelentős kutatási aktivitást mutatnak az SDG-kkal kapcsolatos területeken.

A dendrogram távolságai az intézmények közötti hasonlóság mértékét jelzik. A kisebb távolságok – például az Eötvös Loránd Tudományegyetem és a Budapesti Műszaki és Gazdaságtudományi Egyetem között – szorosabb kutatási fókuszot és hasonló publikációs stratégiát tükröznek. Ezzel szemben a nagyobb távolságok – például az Állatorvostudományi Egyetem és a Semmelweis Egyetem között – eltérő kutatási prioritásokat és teljesítményt mutatnak. A dendrogram világosan bemutatja az egyetemek kutatási fókuszában és fenntarthatósági célokhoz való hozzájárulásában fennálló különbségeket. Az egyes klaszterek azt mutatják, hogy az intézmények közötti eltéréseket elsősorban a kutatási aktivitás intenzitása és az SDG-kel kapcsolatos publikációk koncentrációja határozza meg. Ezek az eredmények kulcsfontosságúak a magyar egyetemek kutatási stratégiáinak értékelése és a fenntarthatósági célokhoz való hozzájárulásuk megértése szempontjából.

A kutatás során rendszerszintű visszatekintést végeztünk a kutatási kérdésekre, minden kérdést újra megvizsgálva, és az eredményeket az eredeti célkitűzésekkel összevetve. Ezt a folyamatot arra használtuk, hogy értékeljük a magyar egyetemek előrehaladását és hozzájárulását az SDG-k eléréséhez.

K1a. Milyen mértékű növekedés tapasztalható az SDG-khez kapcsolódó publikációk számában a magyar egyetemeken 2019 és 2023 között? A vizsgálat jelentős növekedést azonosított az SDG-khez kapcsolódó publikációk számában a magyar egyetemeken. Az SDG-kapcsolódó publikációk száma 2019-ben 3218 volt, amely 2023-ra 5715-re emelkedett, ami 77%-os növekedést jelent. A legjelentősebb növekedés az egyházi fenntartású egyetemeken (132%) volt megfigyelhető, ezt követték a modellváltó egyetemek (80%) és az állami egyetemek (62%). Ezek az eredmények azt

sugallják, hogy a magyar egyetemek kutatási produkciója egyre inkább az SDG-k irányába mozdul el.

K1b. Mely egyetemek mutatták a legjelentősebb növekedést az SDG-khez kapcsolódó publikációk számában? A Semmelweis Egyetem, a Budapesti Műszaki és Gazdaságtudományi Egyetem, valamint a Szegedi Tudományegyetem mutatta a legjelentősebb növekedést az SDG-khez kapcsolódó kutatási teljesítmény terén. Különösen figyelemre méltó, hogy a Semmelweis Egyetem kimagaslóan teljesített az SDG 3 területén, jelentős mértékben hozzájárulva az SDG-k publikációs számához. A kisebb intézmények, mint a Károli Gáspár Egyetem és az Eszterházy Károly Katolikus Egyetem mérsékeltebb, fokozatos növekedést mutattak az SDG-vel kapcsolatos publikációkban.

K2a. Milyen fókuszú publikáció emelkedik ki az SDG-khez kapcsolódó összes publikáció közül mind mennyiségileg, mind hivatkozási szempontból? A legkiemelkedőbb publikációk az SDG 3 keretein belül jelentkeztek, amelyek 11656 cikket foglaltak magukban, és elérték a legmagasabb hivatkozási hatást. Ebben a témakörben a Semmelweis Egyetem és a Debreceni Egyetem járultak hozzá leginkább. Az SDG 3 egészségügyre helyezett hangsúlya összhangban áll a globális tudományos prioritásokkal, így szélesebb körű láthatóságot és nagyobb társadalmi hatást eredményez. Továbbá, az SDG 4 és az SDG 13 témájú publikációk interdiszciplináris jellegükkel és magas hivatkozási rátáikkal tűntek ki.

K2b. Hogyan oszlik meg az adott SDG-hez kapcsolódó publikációk száma az egyetemek között? A Semmelweis Egyetem vezető intézményként azonosítható az SDG 3 kutatási területén, összesen 4088 publikációval, míg ezt követi a Debreceni Egyetem 1756 publikációval. Ezek az adatok azt tükrözik, hogy ezek az intézmények stratégiai fókusza az egészségügyre és a biomedikai kutatásokra irányul. Más egyetemek, például a Szegedi Tudományegyetem és a Pécsi Tudományegyetem szintén jelentős hozzájárulást tettek ehhez a területhez, bár publikációik száma viszonylag alacsonyabb.

K3a. Milyen tényezők befolyásolják, hogy egy egyetem SDG-khez kapcsolódó publikációi magas hivatkozási rátát érnek el? Az olyan intézmények, mint a Semmelweis Egyetem, a Szegedi Tudományegyetem és a Debreceni Egyetem kimagasló teljesítményt mutattak erős kutatási hálózataik és az olyan SDG-területekre való fókuszuk révén, mint az egészségügy és a klímavédelem, ahol a hivatkozási arányok magasak.

K3b. Milyen stratégiák alkalmazhatók annak érdekében, hogy növeljék azon egyetemek láthatóságát és hatását, amelyek kevesebb hivatkozást érnek el az SDG területén? A kisebb intézmények, mint a Károli Gáspár Egyetem és a Budapesti Gazdasági Egyetem, előnyre tehetnek szert azáltal, ha bővítik együttműködéseiket az olyan hazai és külföldi egyetemekkel, kutatóhálózatokkal, amelyek erős SDG-fókuszú és hivatkozású kutatásokhoz köthetőek, illetve interdiszciplináris megközelítéseket alkalmaznak az átfedő, de szorosan kötődő területeken.

K3c. Hogyan járulhat az egyetemek profilja vagy kutatási fókusza az SDG-khez kapcsolódó publikációk hivatkozási rátájához adott témákban? A kutatás rámutat, hogy azok az egyetemek,

amelyek specializált kutatási profilokkal rendelkeznek – például az egészségügyi területen a Semmelweis Egyetem (SDG 3) vagy a műszaki tudományok területén a BME (SDG 7 és SDG 9) – magasabb hivatkozási teljesítményt érnek el. Ezzel szemben azok az intézmények, amelyek szélesebb körű vagy kevésbé célzott kutatási fókuszúak, alacsonyabb hatást produkálnak. Ezek az eredmények azt jelzik, hogy az intézmények erősségeikhez igazított SDG-fókusz növeli mind a publikációs teljesítményt, mind az idézettségi hatást.

Az eredmények rámutatnak arra, hogy bár a publikációk száma növekszik, az SDG-kkel kapcsolatos kutatások besorolása nagymértékben függ az intézményi profiloktól és a nemzetközi rangsorok által befolyásolt stratégiáktól. Hazelkorn (2018) megállapítása szerint a rangsorok hatása azt eredményezi, hogy egyes intézmények az „egyedi” SDG-területeket részesítik előnyben, míg mások átfogóbb megközelítést alkalmaznak.

KÖVETKEZTETÉSEK

Az empirikus vizsgálat alapján megállapítható, hogy a magyar egyetemek rangsorbeli helyezésének alakulását jelentős mértékben befolyásolja a nemzetközi publikációs teljesítmény, különösen a nemzetközi együttműködésben született publikációk aránya. A nemzetközi kooperációban végzett kutatások pozitív korrelációt mutatnak a rangsorokban való előrébb jutással, ugyanakkor az adatok arra is rávilágítanak, hogy az együttműködések mértéke egyetemenként jelentős eltéréseket mutat.

Az elemzés során az is kiderült, hogy az egyes rangsorok különböző súllyal kezelik a tudományos teljesítmény indikátorait, ami eltérő helyezéseket eredményezhet ugyanannak az intézménynek esetében. Ez a megállapítás óvatosságra int a rangsorok alapján történő általános értékelésben. További fontos eredmény, hogy a publikációs aktivitás nem minden esetben jár együtt a magasabb idézettségi mutatókkal. Ez arra utal, hogy a kutatások hatásosságát nem lehet kizárólag a mennyiségi indikátorok alapján megítélni, hanem a kutatások minőségi aspektusait is érdemes figyelembe venni. Az elemzés nem támasztja alá egyértelműen, hogy a publikációs teljesítmény növekedése önmagában jelentős pozíciójavulást eredményezne a rangsorokban. A rangsorbeli mozgás komplex tényezőrendszer függvénye, amelyben a publikációs teljesítmény mellett más változók – például nemzetközi láthatóság, oktatási környezet, finanszírozás – is szerepet játszhatnak.

Összességében a vizsgálat rámutat arra, hogy a magyar egyetemek nemzetközi teljesítményének értékelésekor célszerű a rangsorokat kritikai szemlélettel kezelni, és figyelembe venni azok módszertani sajátosságait, valamint a publikációs stratégiák intézményi különbségeit. A jövőbeni kutatásokhoz megfogalmazható javaslatok: (1) *Módszertani fejlesztések*: Érdemes a kvalitatív módszerek – például interjúk és eseteleírások – bevonása annak érdekében, hogy az SDG-kkel kapcsolatos intézményi stratégiák mögötti tényezőket is feltárjuk. (2) *Nemzetközi összehasonlítás*: Célszerű a magyar egyetemeket más, hasonló profilú országok intézményeivel is összevetni, hogy jobban megérthessük a nemzetközi trendeket. (3) *Tudománypolitikai kapcsolatok vizsgálata*: További

kutatások szükségesek annak érdekében, hogy feltérképezzük, a tudományos publikációk miként járulnak hozzá a fenntarthatósági döntéshozatalhoz a gyakorlatban.

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MELLÉKLET

1. táblázat: Az ENSZ Fenntartható Fejlődési Céljai (SDG-k).
Table 1. The UN Sustainable Development Goals (SDGs)

Sorszám	SDG-célok	A célok jelentése
SDG 1	A szegénység felszámolása.	A szegénység minden formájának megszüntetése a világon mindenhol.
SDG 2	Az éhezés megszüntetése.	Az éhínség megszüntetése, élelmiszer-biztonság létrehozása, az élelmezés fejlesztése és fenntartható mezőgazdaság létrehozása.
SDG 3	Jó egészség.	Egészséges élet biztosítása és jólét megteremtése minden korosztályban élő minden egyes ember számára.
SDG 4	Minőségi oktatás.	Átfogó és igazságos minőségi oktatás megteremtése és egész életen át folytatott tanulmányok lehetőségének létrehozása mindenki számára.
SDG 5	Nemek közötti egyenlőség.	Nemek közötti egyenlőség létrehozása, és minden nő és lány felemelkedésének elősegítése.
SDG 6	Tiszta víz és köztisztaság.	Fenntartható vízgazdálkodás, a vízhez és közegészségügyhöz való hozzáférés biztosítása minden ember számára.
SDG 7	Újrahasznosítható és megfizethető energia.	Megfizethető, megbízható, fenntartható és modern energia biztosítása mindenki számára.
SDG 8	Jó munkalehetőségek és gazdaságok.	Hosszan tartó, átfogó és fenntartható gazdasági növekedés létrehozása, teljes és eredményes foglalkoztatás, valamint méltó munka biztosítása mindenki számára.
SDG 9	Innováció és jó infrastruktúra.	Alkalmazkodó infrastruktúra kiépítése, átfogó és fenntartható iparosodás megteremtése, valamint az innováció támogatása.
SDG 10	Egyenlőtlenség csökkentése.	Egy országon belüli és országok közötti egyenlőtlenségek csökkentése.
SDG 11	Fenntartható városok és közösségek.	Fenntartható, befogadó, biztonságos és alkalmazkodó városok és más emberi települések létrehozása.
SDG 12	A források felelősségteljes használata.	Fenntartható fogyasztási és termelési szokások kialakítása.
SDG 13	Fellépni az éghajlatváltozás ellen.	Gyors cselekedetek a klímaváltozás és hatásai leküzdésének érdekében.
SDG 14	Fenntartható óceánok.	A fenntartható fejlődés érdekében az óceánok, tengerek és tengeri erőforrások megőrzése és fenntartható használata.
SDG 15	Fenntartható földhasználat.	A Föld ökoszisztémáinak fenntartható használata, fenntartható erdőgazdálkodás, az elsivatagosodás leküzdése, a talaj degradációjának visszafordítása, valamint a biodiverzitás csökkenésének megállítása.
SDG 16	Béke és igazság.	A fenntartható fejlődés érdekében békés és befogadó társadalmak létrejöttének elősegítése, mindenki számára elérhető igazságszolgáltatás biztosítása, és minden szinten hatékony, felelősségre vonható és befogadó intézmények létrehozása.
SDG 17	Partnerség a fenntartható fejlődésért.	A végrehajtás módjainak biztosítása és a fenntartható fejlődés globális partnerségének felélesztése.

2. táblázat: A kutatásban szereplő egyetemek megnevezése és típusa.

Table 2. The names and abbreviations of the universities included in the research.

Rövidítések	Egyetem neve	Egyetem típusa
ÁOE	Állatorvostudományi Egyetem	Modellváltó
BGE	Budapesti Gazdasági Egyetem	Modellváltó
BME	Budapesti Műszaki és Gazdaságtudományi Egyetem	Állami
BCE	Budapesti Corvinus Egyetem	Modellváltó
DE	Debreceni Egyetem	Modellváltó
EKKE	Eszterházy Károly Katolikus Egyetem	Egyházi
ELTE	Eötvös Loránd Tudományegyetem	Állami
KRE	Károli Gáspár Református Egyetem	Egyházi
MATE	Magyar Agrár- és Élettudományi Egyetem	Modellváltó
ME	Miskolci Egyetem	Modellváltó
NKE	Nemzeti Közszolgálati Egyetem	Állami
ÓE	Óbudai Egyetem	Modellváltó
PE	Pannon Egyetem	Modellváltó
PPKE	Pázmány Péter Katolikus Egyetem	Egyházi
PTE	Pécsi Tudományegyetem	Modellváltó
SE	Semmelweis Egyetem	Modellváltó
SZE	Széchenyi István Egyetem	Modellváltó
SZTE	Szegedi Tudományegyetem	Modellváltó

3. táblázat: A publikációk teljes száma, az SDG 1–16-hoz kapcsolódó publikációk száma és az SDG 1–16 publikációk aránya 2019 és 2023 között.

Table 3. The total number of publications, the number of publications related to SDGs 1-16, and the proportion of publications related to SDGs 1-16 between 2019 and 2023.

Egyetem	Publikációk száma					SDG 1–16 publikációk száma					SDG-publikációk aránya %					Változás 2019–2023 (II-I)
	2019	2020	2021	2022	2023	2019	2020	2021	2022	2023	2019 (I.)	2020	2021	2022	2023 (II.)	
ÁOE	121	152	158	196	222	41	42	52	76	76	34%	28%	33%	39%	34%	0%
BGE	56	58	100	98	146	25	27	48	46	69	45%	47%	48%	47%	47%	3%
BME	1782	1689	1703	1845	1744	355	406	431	494	476	20%	24%	25%	27%	27%	7%
BCE	312	322	396	488	509	126	143	150	194	238	40%	44%	38%	40%	47%	6%
DE	1412	1559	1650	1720	1731	414	540	631	665	678	29%	35%	38%	39%	39%	10%
EKKE	81	125	172	119	166	16	26	29	24	44	20%	21%	17%	20%	27%	7%
ELTE	1949	2149	2157	2436	2536	279	401	398	498	532	14%	19%	18%	20%	21%	7%
KRE	37	59	75	84	141	3	9	15	18	39	8%	15%	20%	21%	28%	20%
MATE	571	749	928	951	991	210	260	385	424	434	37%	35%	41%	45%	44%	7%
ME	338	382	433	465	583	100	104	117	159	216	30%	27%	27%	34%	37%	7%
NKE	89	119	173	239	211	38	49	61	88	82	43%	41%	35%	37%	39%	-4%
OE	316	414	490	631	815	90	145	159	240	272	28%	35%	32%	38%	33%	5%
PE	321	396	413	407	407	89	128	131	147	144	28%	32%	32%	36%	35%	8%
PPKE	194	228	218	222	230	40	38	43	47	54	21%	17%	20%	21%	23%	3%
PTE	892	1059	1204	1294	1220	286	386	463	494	501	32%	36%	38%	38%	41%	9%
SE	1375	1591	1859	1874	1885	658	796	884	966	964	48%	50%	48%	52%	51%	3%
SZE	195	215	260	353	625	49	69	96	127	267	25%	32%	37%	36%	43%	18%
SZTE	1426	1622	1786	1790	1677	399	542	579	598	629	28%	33%	32%	33%	38%	10%
Összesen/ Átlag	11467	12888	14175	15212	15839	3218	4111	4672	5305	5715	28%	32%	33%	35%	36%	8%

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4. táblázat: Az SDG 1–16-hoz kapcsolódó publikációk eloszlása az egyetemeken 2019 és 2023 között.

Table 4. The proportion of publications related to SDGs 1–16 across universities between 2019 and 2023.

Egyetem	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16
AOE	0	25	166	4	0	9	23	5	1	1	20	12	11	7	42	2
BGE	7	7	29	38	3	10	7	82	37	24	20	57	17	1	6	14
BME	18	27	356	82	15	111	608	135	575	38	533	209	186	26	27	30
BCE	67	51	127	76	46	16	58	224	152	178	60	105	77	3	30	106
DE	38	248	1756	117	44	134	172	216	165	72	141	159	183	38	254	70
EKKE	4	21	18	21	4	9	16	14	5	4	11	21	26	2	44	5
ELTE	28	83	804	173	83	122	178	113	129	109	178	110	153	26	193	178
KRE	2	1	32	19	5	0	0	13	1	12	2	1	0	0	0	15
MATE	38	372	223	75	16	218	218	295	206	64	155	266	210	110	321	30
ME	17	21	119	25	0	84	193	65	192	30	53	76	59	13	14	31
NKE	7	14	48	17	9	43	37	55	42	34	41	24	24	1	19	63
OE	3	41	266	75	4	48	197	89	193	15	115	62	52	9	22	17
PE	5	21	131	36	3	85	160	54	136	16	67	73	65	24	36	9
PPKE	3	1	101	6	8	5	18	18	14	24	13	4	2	0	1	37
PTE	23	53	1460	76	26	61	77	152	95	66	133	92	44	15	111	62
SE	16	27	4088	57	24	12	18	16	25	52	11	18	8	1	8	52
SZE	16	61	92	47	3	34	73	114	197	36	123	111	63	4	22	16
SZTE	32	85	1840	99	46	134	177	97	108	81	127	87	135	27	139	58
Összesen	324	1159	11656	1043	339	1135	2230	1757	2273	856	1803	1487	1315	307	1289	795

5. táblázat: Az SDG 1–16 publikációk idézéseinek száma az egyetemeken 2019 és 2023 között.

Table 5. The number of citations to publications related to SDGs 1–16 across universities between 2019 and 2023.

Egyetem	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	Átlag
ÁOE	ND.	5,88	9,66	3,00	10,67	10,56	9,65	13,00	5,00	7,00	49,25	17,00	10,91	17,71	11,88	15,50	10,39
BGE	6,57	4,43	13,76	4,18	4,33	7,30	4,86	9,76	12,08	5,21	9,80	6,96	1,24	6,00	13,83	11,36	6,76
BME	4,67	9,04	11,79	6,74	3,80	14,99	13,94	14,76	13,13	6,21	11,30	13,89	16,20	23,92	9,81	18,93	8,94
BCE	7,48	16,76	15,69	6,59	4,93	13,63	16,31	9,83	13,93	12,30	12,75	14,02	15,29	4,00	12,73	6,50	7,88
DE	9,74	16,83	18,67	6,87	3,91	12,59	11,57	17,09	13,95	8,79	8,43	16,66	16,16	10,32	17,72	4,99	13,30
EKKE	3,00	5,19	4,22	4,05	0,00	3,67	8,56	8,79	3,00	0,50	6,36	4,05	10,15	4,50	10,66	2,80	11,20
ELTE	11,04	8,93	16,63	5,84	17,00	11,34	16,44	9,71	8,14	8,76	10,85	9,30	18,41	14,12	11,54	9,48	14,38
KRE	11,50	0,00	2,88	1,58	0,80	NA.	NA.	2,31	6,00	2,92	1,50	6,00	NA.	NA.	NA.	3,20	2,76
MATE	13,63	11,04	11,01	8,21	9,50	10,43	13,60	15,53	18,58	9,20	11,59	17,17	11,52	11,57	10,08	7,17	11,46
ME	12,88	3,62	13,22	11,08	NA.	14,60	9,53	7,00	7,91	5,07	10,04	10,33	15,24	8,38	12,71	2,77	6,86
NKE	4,00	14,50	16,85	6,59	7,44	8,86	15,70	7,00	16,40	6,97	10,78	18,00	17,58	7,00	10,53	2,92	6,84
ÓE	11,67	17,71	13,03	7,79	3,75	45,50	16,80	13,56	10,88	3,93	29,10	22,15	27,23	10,22	31,59	5,65	10,43
PE	21,00	16,57	13,68	8,97	50,00	11,68	16,44	15,24	12,70	12,38	10,67	11,07	15,17	15,67	18,00	5,44	10,06
PPKE	1,00	1,00	9,84	10,00	9,50	6,80	8,50	1,83	14,07	5,25	8,85	20,25	0,50	NA.	4,00	1,24	9,42
PTE	7,83	17,64	16,60	5,76	12,88	17,72	9,01	6,01	8,08	6,74	10,26	6,40	18,14	38,87	14,24	8,42	11,59
SE	28,69	13,07	29,32	46,96	7,79	14,00	19,56	33,31	13,36	20,10	73,18	46,17	8,63	7,00	9,38	197,08	20,56
SZE	6,25	11,93	7,10	3,53	NA.	9,74	5,45	8,39	12,30	12,61	7,16	10,63	5,10	21,00	10,36	10,00	6,99
SZTE	7,78	13,07	16,87	8,57	7,59	12,26	20,51	11,05	21,66	6,23	15,11	15,68	21,61	10,89	15,87	5,28	14,43
Átlag	10,00	12,85	20,71	8,87	9,58	13,63	14,03	11,93	12,94	9,34	12,80	13,95	15,68	14,19	13,56	19,44	12,70
Min	1,00	0,00	2,88	1,58	0,00	3,67	4,86	1,83	3,00	0,50	1,50	4,05	0,50	4,00	4,00	1,24	2,76
Max	28,69	17,71	29,32	46,96	50,00	45,50	20,51	33,31	21,66	20,10	73,18	46,17	27,23	38,87	31,59	197,08	20,56

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The Caspian Sea Basin: Legal, Geopolitical, and Environmental Issues

ABSTRACT

The Caspian Sea basin, rich in energy resources, holds strategic importance both among the littoral states and on the international level. Although it lacks access to the open oceans, its abundant hydrocarbon reserves contribute significantly to Europe's energy security and play an important role in maritime transport among the countries of the region—factors that further enhance the sea's significance. However, the legal status of the Caspian Sea has long been a subject of debate. Following the collapse of the USSR, issues emerged concerning the delimitation of borders between the littoral states and the utilization of the sea's resources. This long-standing dispute was only resolved on August 12, 2018, at a summit held in Aktau, Kazakhstan, where the five littoral states (Azerbaijan, Russia, Kazakhstan, Turkmenistan, and Iran) participated and signed the “Convention on the Legal Status of the Caspian Sea.” The primary aim of this study is to clarify the legal status of the Caspian Sea and to examine the related challenges that have arisen over time.

Keywords: The Caspian Sea Basin, littoral states, cooperation, legal status.

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INTRODUCTION

The Caspian Sea is considered one of the world's richest regions in terms of oil and gas reserves. With a total area of approximately 371,000 km² and significant geostrategic importance, it is the world's largest enclosed inland body of water. A key factor—arguably the most important—that enhances the strategic relevance of the Caspian Sea is its abundant hydrocarbon resources (Shafiyev, 2001). Among the littoral countries, Azerbaijan, Kazakhstan, and Turkmenistan possess substantial energy deposits. The Shah Deniz and Azeri–Chirag–Gunashli fields in Azerbaijan, the Kashagan field in Kazakhstan, and the Galkynysh field in Turkmenistan are regarded as major energy sources (Figure 1).

Figure 1. Boundaries of the Caspian Sea energy infrastructure among the littoral states.



Source: U.S. Energy Information Administration, U.S. Geological Survey, IHS EDIN

The transportation of oil from energy fields on the Azerbaijani coast of the Caspian Sea to Europe plays a vital role in ensuring energy security. Accordingly, on September 20, 1994, the “Contract of the Century” was signed in Baku with the participation of eight countries and thirteen international companies for the joint development of the Azeri–Chirag–Gunashli fields in the Azerbaijani sector of the Caspian Sea (Çelikipala & Veliyev, 2015). The implementation of the Baku–Tbilisi–Ceyhan

pipeline further increased interest in both Azerbaijan and the Caspian region. A Joint Declaration was signed between Azerbaijan and the European Commission to ensure the long-term sustainability of this project. At a 2011 meeting in Baku, it was decided to bring gas reserves from the Caspian region, Central Asia, and the Middle East to the European market via the Southern Gas Corridor (Socor, 2014). All these developments have significantly elevated the global importance of the Caspian Sea.

Another factor contributing to the Caspian Sea's strategic significance is its role as a major transport corridor in international trade. The fact that the "One Belt, One Road" initiative, launched by China in 2013, passes through Central Asia and the South Caucasus via the Caspian Sea has further enhanced its geopolitical relevance (Rice, 2023). The decline of Russia's reliability as a transit route following the Russia–Ukraine crisis has strengthened the position of both the South Caucasus region and the Caspian Sea basin within the framework of the "One Belt, One Road" project connecting China and Europe. This initiative is expected to transform the Caspian Sea into one of the world's key transport hubs, while also accelerating trade cooperation among neighboring countries.

Each of the littoral states (Azerbaijan, Russia, Kazakhstan, Turkmenistan, and Iran) has a distinct approach to the Caspian Sea, shaped by its geographical position, energy resources, their exploitation, and priorities in international relations. Following the collapse of the USSR, the borders of the Caspian Sea were redrawn, bringing the issue of energy resource utilization to the forefront. This reconfiguration gave rise to a number of contentious issues. Despite these disputes, the legal status of the Caspian Sea is governed by the "Convention on the Legal Status of the Caspian Sea," signed on August 12, 2018, in Aktau, Kazakhstan. The positions of the littoral states regarding the sea's legal framework are primarily regulated by this convention.

The primary objective of the submitted research paper is to analyze the legal status of the Caspian Sea and to address the controversial issues among the littoral states within the framework of economic cooperation. The specific objectives of the research are as follows:

- To determine the global and regional significance of the Caspian Sea in terms of energy resources and transport routes;
- To identify the differing positions of the littoral states regarding the Caspian Sea and to highlight the emerging challenges;
- To examine the main provisions of the Convention on the Legal Status of the Caspian Sea and to assess the overall outcomes of this agreement.

METHODS

A number of research methods were applied in this study, including the principle of historicity and comparative analysis. The findings indicate that the determination of the legal status of the Caspian Sea and the utilization of its resources became a contentious issue among the littoral states following the collapse of the USSR. Several obstacles have hindered this process, including:

- Disputes over the delimitation of maritime boundaries and the use of energy resources among the littoral states;

- The biased positions of Russia and Iran in this matter;
- The potential establishment of military bases in the Caspian Sea and the risk of its transformation into a military training zone.

The research drew upon literature in Azerbaijani, Russian, and English, along with various documents and internet sources. The reviewed literature addresses the resolution of problems that arose during the process of determining the legal status of the Caspian Sea and highlights efforts to promote cooperation among the littoral states. Although numerous meetings were held among the coastal countries over the years, the legal status of the Caspian Sea remained unresolved for a long time.

The eventual adoption of the Convention was made possible by improved mutual relations and cooperation among the littoral states, as well as by a shared interest in ensuring peace and security in the Caspian region. The initiative by Azerbaijan to transport Caspian energy resources to Europe, along with growing Western interest, also had a positive effect on the development of joint cooperation among the littoral countries.

The determination of the legal status of the Caspian Sea remained a controversial issue for many years, despite numerous meetings held by the littoral states to address it. The eventual adoption of the Convention was driven by improved mutual relations and cooperation among the littoral states, as well as the shared interest in achieving peace and security in the Caspian region. The transportation of Caspian energy resources to Europe—initiated by Azerbaijan—and the West's growing interest in the region also had a positive impact on the establishment of joint cooperation. As a key finding of the research, it was determined that the Convention signed by the littoral states at the Aktau meeting on August 12, 2018 constitutes the final legal framework for defining the status of the Caspian Sea. It was also concluded that this legal document should serve as the primary reference for resolving future disputes.

RESULTS

Early historical documents on the legal status of the Caspian Sea

The initial provisions regarding the legal status of the Caspian Sea were partly reflected in the Treaties of Petersburg (1723), Resht (1731), Gulustan (1813), and Turkmenchay (1828). However, these documents did not address the concept of the Caspian Sea's "legal status" from a formal legal perspective. Rather, they primarily granted significant privileges to the Russian Empire concerning activities in the Caspian Sea.

During the Soviet era, the Caspian Sea was effectively divided between the USSR and Iran. Article 3 of the Russian–Iranian (Qajar) Treaty on the legal status of the Caspian Sea—signed in Moscow on February 26, 1921, by Georgy Chicherin on behalf of Russia and P. Garakhan-Mamluk on behalf of Iran—states:

“Both parties negotiating at a high level agree to accept the borderline determined by the border commission in 1881 as the water border between Iran and Russia. This border must

be protected and inviolable” (Ministry of Foreign Affairs of the Russian Federation, 2018). The perception of the Caspian Sea as a Soviet-Iranian sea was also reflected in the treaties “On Trade, Maritime Affairs, and Settlement” signed in 1935 (Treaty of Settlement, Commerce and Navigation between the Union of Soviet Socialist Republics and Iran), and “On Trade and Maritime Affairs” signed in 1940 (Treaty of Commerce and Navigation between the Union of Soviet Socialist Republics and Iran).

In 1970, the issue of dividing the portion of the Caspian Sea under Soviet control into separate sectors was first discussed and implemented by the USSR Ministry of Oil Industry. According to this division, the Caspian Sea was partitioned into the sectors of the Russian SFSR, Kazakh SSR, Azerbaijani SSR, Turkmen SSR, and Iran, based on the land borders of the Soviet Union. This division followed the principle of the median line, a concept derived from the legal and geographical context of the Caspian Sea and widely accepted in international legal practice.

Following the collapse of the USSR, the Caspian Sea was redistributed among five newly independent states: Azerbaijan, Russia, Kazakhstan, Turkmenistan, and Iran. As a result, the previous treaties concerning the Caspian’s legal status became obsolete, and several contentious issues emerged. The newly established littoral states, formerly part of the Soviet Union, unilaterally asserted their sovereign rights over various sections of the Caspian Sea and declared their national positions regarding the division of the sea into sectors.

The final provision on the legal status of the Caspian Sea was only established with the signing of the Convention on the Legal Status of the Caspian Sea by the five littoral states at a summit held in Aktau, Kazakhstan, in August 2018. In addition to resolving the legal status of the sea, the Convention aims to regulate the exploitation of its natural resources, promote environmental protection, and prevent conflict in the region.

Problems arising from the status of the Caspian Sea

After the collapse of the Soviet Union, new questions arose regarding the status of the Caspian Sea, as well as its bottom, surface, and natural resources: Should all the Caspian Sea’s resources be owned by all the littoral states, or should they be divided equally among them, and on what basis should this be done? In terms of hydrocarbon reserves, the Caspian Sea can be compared to the Persian Gulf. In this regard, all the Caspian littoral states are working to study the seabed and exploit the Caspian’s resources. The newly formed littoral states on the territory of the former USSR unilaterally declared their sovereign rights over various parts of the Caspian Sea and declared their position on the division of the Caspian into national sectors.

Since 1992, efforts have been made to form and find solutions to multilateral relations on the status and regime of the use of the Caspian Sea (including problems related to shipping, fisheries, ecology, and economic issues, especially the use of rich hydrocarbon resources). The Islamic Republic of Iran was the first country to make an official statement on the problem that had arisen in this direction. The Russian Federation, which was closely following the events taking place in the post-Soviet

region, tried to direct the process to its own interests. As for the other littoral states, each of them put forward its own considerations and proposals. For example, Iran, in order to regulate the issue of collective study of the Caspian, first put forward a proposal to establish a cooperation organization to regulate the problems of the Caspian Sea within the framework of the intergovernmental conference of the Economic Cooperation Organization (February 1992). By putting forward this proposal, former Iranian President Hashemi Rafsanjani was trying to attract the attention of the countries of the region, as well as the Western world, to Iran, which had gradually withdrawn from world politics. In addition, the Islamic Republic of Iran initiated the establishment of the “Cooperation of the Caspian Sea States” organization with the aim of expanding cooperation with the Caspian littoral states (Zhiltsov, 2003). That organization envisaged the unity of states such as Russia, Turkmenistan, Kazakhstan, Azerbaijan, and Iran, and the protection of the Caspian ecology, the proper use of its natural resources, and joint cooperation of the member states.

The issue of a concrete and practical approach to the problem related to the status of the Caspian was brought to the agenda within the framework of a special conference held in Tehran in September–October 1992. At that event, a proposal was put forward to establish an international organization to regulate the problems of the Caspian Sea (Nasibli, 2000). The delegation of the Republic of Azerbaijan put forward the issue of the international status of the Caspian Sea as a proposal at the Tehran Conference of the five Caspian littoral states held in October 1992.

The first conference of the Caspian littoral states with the participation of top experts (ecologists, biologists, lawyers, etc.) was held in Rasht, Iran, in October 1993. The conference revealed that there are very different conventions on the Caspian problem among the littoral states. At this conference, the proposal of the Azerbaijani representative to determine the status of the Caspian as a “coastal lake” was met with serious objections from the Russian and Iranian delegations. Thus, the Iranian and Russian sides insisted on applying the provisions of the bilateral agreements signed in 1921 and 1940 regarding the delimitation and use of the Caspian Sea to all five littoral states (Shafiyev, 2001). Iran, which has been considered one of the two states that own the Caspian for many years, has a very contradictory relationship with the new states in the region and a complex approach to the status of the Caspian in general. It should be noted that Iran’s geopolitical interests are more important than its economic interests in the Caspian Sea. The main point of interest to official Tehran is not whether the Caspian Sea is perceived as a sea or a lake, but rather ensuring Iran’s security and eliminating the potential threat from the West, which has become more active in the region. Economic interests are secondary for Tehran, at least because Iran has richer deposits in the Persian Gulf. Iran is very sensitive to the activation of foreign forces in the region. Naturally, Iran’s cool relations with the West, and especially the United States, play an important role here. The fact that Iran and Russia take the same position in approaching geopolitical processes in the region is based on this factor (Hasanov, 2005). However, Russia is also trying to limit the participation of third parties in the Caspian Sea, citing security issues as a basis.

There was a revival in the principle of approaching the issue of the international legal status of the Caspian Sea with the signing of the “Contract of the Century” on September 20, 1994. Nevertheless, Iran and Russia could not hide their jealousy regarding the “Contract of the Century.” As is known, Iran

did not get any share in the “Contract of the Century.” This was not only due to Iran’s dissatisfaction with the contract but also due to the tension in Iran–US relations. The Republic of Azerbaijan, based on the principle of neighborliness with Iran and cooperation in the use of the Caspian Sea, in December 1994 showed a tendency to transfer a certain part (approximately 10%) of its share in the oil contract to Iran (Aliyev, 2003). Thus, the Iranian Oil Industries Engineering and Construction Company (OIEC) participated in two international consortia (the “Shah Deniz field” contract dated June 4, 1996, and the “Lankaran–Talysh offshore structures” contract dated January 13, 1997). However, Iran opposed the Azerbaijani side’s proposal to divide the sea into national sectors and insists on this position to this day. At the same time, this initiative of the Republic of Azerbaijan was not considered acceptable by the US and European companies that joined the contract.

Unlike the Azerbaijani proposal to divide the Caspian into national sectors, Iran has put forward a proposal to divide the Caspian Sea on the basis of the “condominium” principle—the principle of equal use of the bottom and surface of the Caspian, as well as all its resources. This proposal is not acceptable from a legal, scientific, or practical point of view. In recent years, Iran has tended to “soften” its position on the Caspian, hinting that it agrees to a 20% division principle instead of the 50/50 division principle. However, the Republic of Azerbaijan, along with other Caspian littoral states, does not accept this proposal of Iran (Talibli, 2006). The Islamic Republic of Iran considers the political, economic, and military cooperation of the United States with the countries of the South Caucasus and Central Asia to be a serious threat to itself. Therefore, Iranian officials are opposed to the development of US–Azerbaijani relations and the exploitation of the energy and fuel resources of the Caspian Sea by US companies. Naturally, the fact that the United States holds the largest share in the oil consortium in the “Contract of the Century” and the exclusion of the Iranian Oil Company has caused some tension in Azerbaijani–Iranian relations. Competing with Turkey in the Caucasus and Central Asia, Iran is actually helping to strengthen Russia’s position there. This does not mean that there is no competition between them at all. However, Iran and Russia remain strategic rivals in the issue of transit of hydrocarbon resources of the Caspian basin countries. With the commissioning of the main export pipeline Baku–Tbilisi–Ceyhan in 2006, this competition, although somewhat weakened, continues to remain on the agenda (Talibli, 2016).

As can be seen, the discussions on the determination of the legal status of the Caspian Sea have resulted in the emergence of a number of controversial issues among the littoral states. In particular, the biased positions of the Russian and Iranian parties have significantly slowed down the process of determining the legal status of the Caspian Sea for many years. However, the positive results achieved between the littoral states in recent years, as well as the transportation of energy resources from the Caspian Sea to Europe, and the interest of the Azerbaijani, Kazakh, and Turkmen parties in this direction, have played a crucial role in eliminating the problems that have arisen in connection with the determination of the legal status of the Caspian Sea.

Determining the legal status of the Caspian Sea

There have been ongoing meetings and discussions among the littoral states concerning the determination of the legal status of the Caspian Sea, its delimitation and demarcation, as well as joint cooperation and the utilization of its resources. Consequently, the first steps toward cooperation in the Caspian Sea were taken even before the lifting of international sanctions against Iran.

The first initiative for joint cooperation between the riparian states was launched in 2014 during the meeting of Iranian President H. Rouhani and Azerbaijani President I. Aliyev at the World Economic Forum in Davos, Switzerland. The Iranian president emphasized the existence of shared features between the two countries and, therefore, the importance of a developed Azerbaijan for Iran (Valiyev & Mahammadi, 2018).

During the discussions held during the official visit of Azerbaijani President I. Aliyev to Tehran in February 2016, significant attention was paid to cooperation in the Caspian Sea, including the implementation of joint projects for exploring the energy resources of the Caspian and expanding passenger and cargo transportation (Valiyev & Mahammadi, 2018).

At the joint press conference following the meeting, President Aliyev stated: *“We had a very good exchange of views on future cooperation. The issue of joint development of oil and gas fields located in the Caspian Sea was also discussed, and good results are expected. The Caspian Sea is our common wealth. The Caspian Sea should continue to be a sea of cooperation, security and peace”* (President of the Republic of Azerbaijan, 2016).

In July 2016, at the 6th meeting of the Foreign Ministers of the Caspian littoral states in Astana, it was decided to prepare a preliminary draft of the convention by the next Astana summit. During the Baku meeting of the working group on determining the legal status of the Caspian, held in January 2017, it was suggested that the legal status of the Caspian could already be resolved at the next summit of heads of state. Azerbaijani Deputy Foreign Minister Khalaf Khalafov noted that significant progress had been made toward an agreement and stated that extensive work had been done on the draft convention. Iranian Deputy Foreign Minister for the Asia-Pacific Region, Ibrahim Rahimpour, remarked that the ongoing discussions entailed “very complex technical work” and expressed hope that an agreement would be reached in the near future. He also emphasized that some aspects still needed clarification, though the parties were gradually approaching a final agreement (Valiyev & Mahammadi, 2018).

The Convention, comprising 24 articles on the legal status of the Caspian Sea, was signed by President Ilham Aliyev of Azerbaijan, President Nursultan Nazarbayev of Kazakhstan, President Vladimir Putin of Russia, President Hassan Rouhani of Iran, and President Gurbanguly Berdimuhamedov of Turkmenistan on August 12, 2018, during the 5th Summit of the Heads of State of the Caspian Sea, held in the port city of Aktau, Kazakhstan (Official website of the President of the Republic of Azerbaijan, 2018). The Convention addresses legal, geopolitical, economic, and environmental issues.

Article 1 of the Convention states that *The Caspian Sea“ – the body of water surrounded by the land territories of the Parties and outlined on the 1:750,000-scale nautical charts of the General Department of Navigation and Oceanography of the Ministry of Defense of the Russian Federation,*

Saint Petersburg, No. 31003, archive edition of 17.04.1997 published in 1998; No. 31004, archive edition of 04.07.1998 published in 1999; No. 31005, archive edition of 16.11.1996 published in 1998, certified copies of which are attached to this Convention and form an integral part thereof (Law of the Republic of Azerbaijan on ratification of the Convention on the Legal Status of the Caspian Sea, 2019).

It is noteworthy that Article 3 of the Convention prohibits the establishment of any military base in the Caspian Sea and the presence of foreign military vessels. Furthermore, the Caspian littoral countries commit not to use their territory for military purposes against other countries in the region.

The Convention outlines general principles for the division of the Caspian Sea bed and subsoil. A specially designated group is to be established to prepare specific agreements and methodologies for implementation, to be organized at the level of foreign ministers. This issue is of particular importance to the Caspian littoral states, with Iran demonstrating particular sensitivity. Azerbaijan's position on dividing the sea bed and surface into sectors among the parties aligns with international law and is clearly articulated. In this context, the agreements signed between Azerbaijan, Kazakhstan, and Russia are also highly significant.

Experts have put forward prognostic theses regarding both the geopolitical significance of the Aktau summit and the prospects for future cooperation among the littoral states. Above all, they focus on the geopolitical and security implications. The signing of an international document that enables the Caspian states to act collectively on fundamental issues is seen as a commendable step amid complex geopolitical conditions. The littoral states now have the opportunity to address potential conflicts independently, based on a formal legal framework (Karimov, 2023).

Experts also underscore the importance of the “Communiqué of the Fifth Caspian Summit” adopted at the end of the summit, in addition to the Caspian Convention. The communiqué states: *“A challenging path has been went by in the summits held on the Caspian Sea—Ashgabat in 2002, Tehran in 2007, Baku in 2010 and Astrakhan in 2014—leading up to today's summit. The main outcome of the Aktau summit on August 12 was the signing of the basic international agreement - the International Convention on the Legal Status of the Caspian Sea by the leaders of the five countries. This document was elaborated on the basis of consensus and consideration of the mutual interests of all parties”* (Law of the Republic of Azerbaijan on ratification of the Convention on the Legal Status of the Caspian Sea, 2019).

At the same time, the leaders of the littoral states agreed to establish special five-party consultation mechanisms to ensure effective implementation of the agreements. The accords reached by the governments concerning enhanced cooperation in fields such as the economy, transport, energy, innovation, tourism, and information are highly welcomed. To this end, the First Caspian Economic Forum was held on August 12, 2019, in Turkmenbashi, Turkmenistan. The forum addressed topics including trade and economic development, the creation of conditions for major projects, the Caspian region's role in the global economy, and investment opportunities in oil and gas, electricity, transport, agriculture, tourism, and other mutually beneficial areas.

Despite some disagreements among the Caspian littoral states, the Convention signed in Aktau is regarded as the definitive document. Nonetheless, not all issues were resolved within it (Efsthathio,

2018). However, the Convention, which was unanimously adopted, serves as the principal legal framework for addressing future challenges and ensuring regional security and economic cooperation.

CONCLUSIONS

As can be seen, the resources of the Caspian Sea were divided among the five littoral states following the dissolution of the USSR. However, the determination of its legal status took a considerable amount of time. The main challenges in defining the legal status of the Caspian Sea were the biased positions of certain parties regarding the delimitation of maritime boundaries and the use of energy resources, as well as the potential transformation of the region through the establishment of military training grounds.

Thus, the signing of the legally significant Convention by the Caspian littoral states in Aktau is expected to have serious geopolitical, cultural, ecological, economic, and communicative consequences. Cooperation on the legal status of the Caspian Sea should foster mutual understanding among the littoral states, prevent the militarization of the sea, and guard against its becoming a target of geopolitical rivalry between great powers.

The best example of such an approach is demonstrated by official Baku. For many years, Azerbaijan has sought to develop relations based on the principles of cooperation, regional prosperity, good neighborliness, and mutual benefit from the Caspian's oil and gas resources. In this regard, existing joint cooperation among the littoral states plays a crucial role in maintaining peace and security in the region and strengthening economic ties.

The decisive role of the Caspian Sea in determining its legal status and ensuring energy security opens new prospects for the littoral countries. At the same time, the implementation of the New Silk Road—the “One Belt, One Road” initiative stretching from China to Europe—and the fact that the Middle Corridor passes through the Caspian Sea further enhance its strategic significance. The realization of this project will not only strengthen economic cooperation among the littoral countries but also on a global scale, with numerous countries set to benefit. All of this once again underscores the importance of the Caspian Sea.

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Territorial Analysis of the Sustainable Urban Development Strategy of the City of Győr

ABSTRACT

Sustainable urban development in Győr has received special attention in recent decades. This study examines the city's sustainable development strategies, with a particular focus on increasing green spaces, improving public spaces and improving the energy efficiency of transport systems. The example of Győr illustrates how urban planning and policies can be shaped according to the principles of sustainability, ensuring an improved quality of life for the population and the conservation of natural resources. The research highlights the importance of cooperation between local government and the community and the role of innovative solutions in promoting sustainable development. The results show that Győr is successfully integrating global sustainability goals into the local context and can serve as a model for other cities.

Keywords: urban development, sustainability, urbanism, local governments

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INTRODUCTION

Sustainable urban development is a comprehensive approach that integrates economic, social, and environmental considerations to create cities that are resilient, efficient, and equitable for current and future generations. It involves a holistic and integrated approach to urban planning and management that seeks to balance economic growth, environmental protection, and social equity. This approach is dedicated to enhancing the quality of urban life by considering ecological, cultural, political, institutional, social, and economic aspects (Yu, 2021). Sustainable urban development focuses on achieving stable economic growth and structural optimization within cities, leading to urbanization and modernization (Wang et al., 2020).

Sustainable urban development strategies are becoming increasingly important to address the myriad challenges posed by rapid urbanization (Enyedi, 2012), climate change and resource depletion (Hungarian Urban Society, 2020). As cities continue to grow at an alarming rate, they face pressing problems such as pollution, inadequate infrastructure and social inequalities. In response, urban planners and policy makers are seeking innovative solutions to create more resilient, efficient and liveable cities. By integrating sustainability principles into urban development, these strategies seek not only to improve the quality of life for current residents (Madarász, 2018), but also to ensure that future generations can thrive in balanced ecosystems.

One key aspect of sustainable urban development is the concept of sustainable urban form, which emphasizes characteristics such as compactness, walkability, high density, public transport dominance, mixed land use, proximity, connectivity, diversity, ecological integration, well-designed spaces, and high environmental standards (Chen et al., 2022). This form of development aims to create cities that are more sustainable by altering physical elements and urban organization to increase urban density (Bikdeli, 2016). Additionally, sustainable urban transformation involves multidimensional and radical changes that steer urban development towards ambitious sustainability goals (McCormick et al., 2013). It emphasizes structural transformation processes that can effectively drive urban development towards sustainability (Fayad, 2022).

In the context of sustainable urbanization, the synergy degree of sustainable urbanization measures the coordinated development and orderly evolution trend of various subsystems within the urbanization system, including demographic change, economic development, spatial structure, environmental quality, and social development (Jiao et al., 2017). Furthermore, the theory of sustainable urban development includes dimensions such as economic, social, and natural sustainability, highlighting the importance of balancing these aspects for overall urban sustainability (Liu, 2021). The evaluation of green transportation systems within urban areas based on sustainable development theory integrates the principles of sustainable development into transportation planning and design (Wang et al., 2019).

Urban agriculture also plays a role in sustainable urban development, with strategies based on theories like the core-periphery theory and multifunctionality of agriculture theory. These strategies aim to promote urban agricultural development and contribute to urban sustainability by integrating urban and rural planning (Tian & Xu, 2012).

In assessing sustainable urban development, it is crucial to consider various tools and methodologies for evaluating the sustainability of urban design. These tools help establish classification parameters for different phases of urban development, temporal and spatial scales of intervention, sustainability dimensions, and stakeholder involvement, enhancing the understanding of sustainable urban development evaluation (Gil & Duarte, 2013). Additionally, addressing environmental risks associated with urban development projects through the application of sustainable development theory can help evaluate the environmental, social, and economic impacts of such projects, paving the way for more sustainable and equitable urbanization practices (Mburu, 2024). Achieving sustainable urban development requires a concerted effort to balance competing interests and prioritize long-term sustainability over short-term gains.

The aim of this paper is to analyze the process, implementation, and expected impacts of sustainable urban development strategies in Hungarian municipalities, particularly in cities with county status. Our analysis is based on the sustainable urban development strategies of Hungarian cities with county rights, with a special focus on Győr (Municipality of Győr City, 2022), as well as on questionnaires and other research and preparatory documents used in their development.

LITERATURE REVIEW

Sustainable Urban Development

Sustainable urban development aims to balance economic growth, social equity, and environmental protection. Since the publication of the Brundtland Report (1987), sustainability has become a central concept in urban development, emphasizing the need to meet present needs without compromising future generations. Pongruengkiat et al. (2023) and Yu (2021) emphasize the importance of a holistic approach integrating economic, social, and environmental aspects. Sustainable urban development requires structural transformations that foster stable economic growth, high quality of life, and environmental equilibrium (Wang et al., 2020; McCormick et al., 2013). Key features of a sustainable urban form include compact urban structures, pedestrian-friendly environments, mixed-use land development, and prioritization of public transport (Chen et al., 2022; Bikdeli, 2016). Assessment tools and sustainability indicator systems (Gil & Duarte, 2013; Sikos & Szendi, 2022; Central Statistical Office, 2021) enable effective monitoring of environmental, economic, and social dimensions of urban progress.

The „green city” concept focuses on ecological integration within urban environments, particularly through the expansion of green spaces, enhancement of ecosystem services, and mitigation of the urban heat island effect. Schmeller (2021) highlights the significance of „tactical urbanism” in creating green spaces, emphasizing flexible, community-driven interventions that make urban areas more sustainable. Green transport system evaluations (Wang et al., 2019) are also integral to green urban development, promoting environmentally friendly mobility and healthier cities. The „Green

Cities Europe” initiative further supports strategies that address climate change and biodiversity preservation, aiming to make urban environments more resilient and sustainable.

The ”smart city” approach enhances urban system efficiency and sustainability through the application of digital technologies and data-driven decision-making. Smart city strategies integrate information and communication technologies (ICT) to optimize transportation, energy supply, public services, and governance (Vácz et al., 2022). According to Fayad (2022), smart urban development is not only about technology but also about creating socially inclusive and environmentally sustainable solutions. Urban agriculture initiatives (Tian & Xu, 2012) and participatory planning models (Gehl, 2010) demonstrate how smart technologies can contribute to urban food security and social cohesion, broadening the scope of smart city innovations.

The ”sponge city” concept addresses challenges posed by climate change, especially in managing urban stormwater. The key idea is to enhance urban areas’ ability to absorb, store, and reuse rainwater naturally. Sponge cities aim to reduce flood risks, conserve water resources, and improve urban livability by integrating green infrastructure such as green roofs, rain gardens, and permeable pavements. Studies by Chen et al. (2022) and Jiao et al. (2017) underline the necessity of enhancing cities’ climate adaptability as a fundamental component of sustainable urban strategies. Sponge city models not only offer environmental benefits but also contribute to economic efficiency and social well-being by lowering infrastructure costs and improving overall urban quality of life.

Sustainable Urban Development in Central and Eastern Europe

Sustainable urban development in Central and Eastern Europe has garnered significant interest and research attention, particularly due to the challenges and opportunities faced by cities transitioning from socialist to capitalist economic systems. Urban planning efforts in this region have been characterized by the incorporation of an environmental agenda and a focus on sustainable development, reflecting the increasing awareness of the importance of sustainable practices amidst political, structural, social, and economic changes (Martín-Díaz et al., 2015). This shift towards sustainability is pivotal in shaping urban policies and management strategies in post-socialist urban societies, where addressing the decline of shrinking cities is crucial for urban revitalization and re-urbanization efforts (Kantor-Pietraga, 2021).

The socio-economic and political changes at the end of the 20th century in Central and Eastern Europe significantly impacted the transformation of urban spaces, especially in industrial and mining towns, underscoring the necessity for innovative approaches to sustainable urban development (Kantor-Pietraga et al., 2021). Moreover, the influence of globalization, internationalization, and societal transformations on urban development and property management has been notably strong in Central and Eastern European countries, highlighting the significance of strategic decision-making in urban development processes (Melnikas, 2005). This dynamic environment has led to the emergence of sustainable management accounting practices and an increasing public awareness of corporate sustainability in the region (Zyznarska-Dworczak, 2018).

Research examining the relationship between economic growth and sustainable development indicators in Central and Eastern Europe has aimed to identify key factors influencing economic growth and sustainability in the region. By analyzing the interplay between economic growth and sustainable development indicators, studies have sought to determine the primary variables shaping the economic landscape of Central and Eastern European countries (Lapinskienė & Tvaronavičienė, 2009). Additionally, the evolution of systems of cities in countries like the Czech Republic, Hungary, and Poland since the mid-20th century has highlighted the process of metropolization and the changing settlement networks in the region, emphasizing the need for comprehensive urban planning strategies (Hajdú et al., 2017; Zdanowska, 2015).

The concept of urban shrinkage and housing in post-socialist cities like Łódź, Poland, has shed light on the relationship between demographic evolution and housing development, emphasizing the complex interplay between systemic transformation and urban development processes in Central and Eastern Europe (Szafrńska et al., 2018). Furthermore, the phenomenon of depopulation in post-industrial regions has raised questions about the potential for urban sustainability in shrinking cities, emphasizing the need for innovative approaches to address demographic shifts and urban planning challenges (Runge et al., 2018).

Understanding the patterns of urbanization in Eastern European cities in comparison to Western trends has provided valuable insights into the unique, convergent, or hybrid nature of urban development in the region (Taubenböck et al., 2019).

In the realm of sustainable urban development, bottom-up movements in Central and Eastern Europe have played a crucial role in advocating for sustainable practices and community-driven initiatives. These movements have been instrumental in shaping urban policies, promoting environmental sustainability, and fostering community engagement in the region (Jacobsson, 2016). Additionally, the exploration of knowledge production and learning for sustainable landscapes in Central and Eastern Europe has underscored the importance of transdisciplinary research and stakeholder engagement in promoting sustainable land use practices and environmental conservation efforts (Angelstam et al., 2013).

In conclusion, sustainable urban development in Central and Eastern Europe is a multifaceted and dynamic process that necessitates a comprehensive understanding of the socio-economic, political, and environmental factors influencing urban landscapes in the region. By integrating sustainable practices, community engagement, and innovative urban planning strategies, cities in Central and Eastern Europe can progress towards creating more resilient, equitable, and environmentally friendly urban environments for present and future generations.

To develop a sustainable urban development strategy in the European Union (EU), it is crucial to address the diverse challenges and opportunities that cities encounter in the region. The EU has emphasized sustainable urban development as a fundamental policy objective, as demonstrated by initiatives like the Aalborg Charter in 1994 and the European Union Strategy for Sustainable Development in 2002 (Dimitrova, 2007). These initiatives highlight the significance of integrating economic, social, and environmental considerations into urban planning and management practices to establish cities that are resilient, efficient, and equitable for all residents.

The use of sustainable urban development strategies is essential in shaping the cities of the future. Numerous examples in Europe and Hungary (Nagy-Szijártó & Szalmáné Csete, 2023) show that integrated and comprehensive approaches are needed to achieve sustainability goals. Such strategies not only help to reduce environmental pressures, but also contribute to improving the quality of life of the population (Lechner Knowledge Centre, 2019).

Focusing on Cities: Municipal Sustainability

The sustainability of cities is of paramount importance, as urban areas are often the epicenter of many environmental, social and economic challenges. With more than half of the world's population living in urban areas, the importance of sustainability in cities is becoming increasingly important for promoting resilience, improving quality of life and ensuring the well-being of future generations.

An essential component of sustainable urban development in the EU involves the adoption of Integrated Sustainable Urban Development Strategies (ISUDS), which have been progressively implemented to tackle the intricate challenges faced by urban areas (Medeiros & Der Zwet, 2019). These strategies advocate for a holistic and integrated approach to urban planning, concentrating on improving residents' quality of life, promoting environmental sustainability, and fostering economic growth. By embracing ISUDS, EU cities can benefit from a comprehensive and coordinated approach to urban development, transitioning from traditional sectoral-focused policies to more integrated and sustainable solutions.

Moreover, the issue of urban sprawl presents a significant obstacle to sustainable urban development in the EU. Research has indicated the necessity for a European de-sprawling strategy to manage urban sprawl, establish targets and boundaries, and utilize land more efficiently (Hennig et al., 2015). By endorsing compact city models over dispersion and sprawl, EU cities can mitigate environmental harm, decrease commuting distances, and enhance the overall urban living standards. Implementing measures to control urban sprawl aligns with the EU's dedication to creating thriving, appealing, and sustainable cities that prioritize environmental sustainability and social inclusion (Hennig et al., 2015).

Regarding urban shrinkage, an emerging concern for European policymaking, EU cities must implement strategies that balance population dynamics, employment opportunities, environmental quality, and social cohesion (Alpek et al., 2016; Bank et al., 2003; Haase et al., 2013; Tésits, 2003, 2005; Tésits & Bokor, 2000; Tésits & Bokor, 2005a,b,c; Tésits & Alpek, 2017; Tésits et al., 2005). Viewing shrinkage as an opportunity to enhance existing residents' quality of life through sustainable urban development initiatives can lead to more resilient and inclusive cities. Through engaging in civic participation and community-driven approaches, EU cities can navigate the challenges of urban shrinkage while promoting sustainable growth and development.

Furthermore, the EU's Europe 2020 strategy underscores smart, sustainable, and inclusive growth as crucial elements for enhancing economies and ensuring long-term prosperity (Issa et al., 2018). By aligning urban development strategies with the objectives of the Europe 2020 strategy, EU cities can

stimulate innovation, competitiveness, and social cohesion while advancing sustainability goals. This integrated approach to urban development emphasizes the importance of balancing economic growth with social and environmental considerations to establish vibrant and sustainable urban environments. Below are some key aspects that highlight the importance of sustainability in urban environments:

Environmental Protection and Resource Conservation

Urban areas significantly contribute to greenhouse gas emissions and environmental degradation (Lechner Knowledge Centre, 2020). Implementing sustainable practices helps mitigate these adverse effects (Eisenhart-Lennert, 2021) by promoting energy efficiency, waste reduction, and natural resource conservation. Strategies such as green building practices, sustainable landscaping, and urban biodiversity initiatives can reduce the ecological footprint of cities and help combat climate change.

Sustainable cities prioritize public health by improving air and water quality, encouraging active transport, and increasing access to green spaces. A well-designed urban environment can reduce pollution-related illnesses, promote physical activity, and provide mental health benefits associated with exposure to nature. By fostering healthy lifestyles, sustainable urban planning contributes to a happier and healthier population.

Urban sustainability extends to social justice and equity. A sustainable approach ensures that all community members have access to essential services, green spaces, and opportunities to participate in decision-making processes. By promoting inclusive urban design, cities can address social inequalities, empower marginalized communities, and foster a sense of belonging, ultimately enhancing social cohesion.

Sustainable urban strategies strengthen local economies (Chikán & Czakó, 2018) by creating green jobs (Bod, 2017) and fostering innovation in sectors such as renewable energy (Tagliapietra & Zachmann, 2020), sustainable transport, and waste management. Investing in sustainable infrastructure not only generates employment opportunities (Köllő, 2015) but also stimulates economic growth by improving business efficiency and reducing operational costs.

Cities are highly vulnerable to climate change impacts, including extreme weather events, rising sea levels, and heatwaves. Sustainable urban strategies are crucial for enhancing cities' adaptive capacity (Newman et al., 2009). Measures such as climate-resilient infrastructure, green roofs, urban parks, and sustainable water management help cities prepare for and respond to climate-related challenges (Rogers & Gumuchdjian, 2011).

Sustainability directly improves urban quality of life (Szirmai, 2012) by fostering healthier, more attractive, and functional living spaces. Well-planned sustainable cities offer affordable housing, efficient public transport, cleaner neighborhoods, and diverse leisure opportunities. These factors contribute to overall well-being and enhance a city's appeal for tourism and investment (Szirmai, 2011).

Sustainable urban strategies emphasize the importance of efficient and accessible public transport systems, reducing reliance on private vehicles and minimizing congestion. Initiatives such as bike-

sharing programs, pedestrian-friendly infrastructure, and multimodal transport systems significantly lower emissions and improve mobility, making cities more livable.

The importance of sustainability in urban environments spans environmental, social, and economic dimensions, necessitating a holistic approach to future urban development. By prioritizing sustainability, cities can create resilient and equitable environments that serve both current and future generations. As urban landscapes continue to evolve, sustainability will remain a fundamental principle in shaping cities capable of thriving amidst modern challenges.

METHODS

The primary source for the research was the questionnaire of the Sustainable Urban Development Strategy of the City of Győr. The questionnaire was distributed among the city's residents and local experts to reflect the specific needs and opinions of the different residential areas. The questionnaire aimed to identify challenges and opportunities in the urban environment and to formulate recommendations in line with sustainable development objectives. The questionnaire covered several different aspects, including:

- The environmental condition of residential areas.
- Transport and infrastructure facilities.
- Accessibility of public spaces and green areas.
- Public perception and awareness of sustainability.
- Local economic opportunities and employment.

The data collected was analysed using qualitative and quantitative methods. Statistical analysis was used to examine the frequency and distribution of responses, while thematic analysis of qualitative responses was used to identify community needs and suggestions.

Categorisation of Győr City Districts

The sustainable urban development strategy of the city of Győr has received considerable attention in recent years, particularly in balancing the dynamic development of the city's areas with environmental sustainability. Different parts of the city have different challenges and opportunities, which the city administration is addressing with different development approaches. The aim of this analysis is to show how the sustainable urban development strategy is being implemented in the different parts of Győr, grouped into three main categories: the city centre and its immediate neighbourhoods, the residential areas and the peripheral areas.

The Sustainable Urban Development Strategy for the City of Győr adopts a comprehensive and multi-faceted approach, taking into account the different character and needs of the different neighbourhoods. The development of the city center and its immediate surroundings is aimed at strengthening the economic and cultural centre, while the sustainability ambitions of the residential areas (Figure 1).

The map displays the urban districts of Győr, Hungary, categorized into three main groups based on color coding:

- Green:** The city center and its connected urban districts. These include districts like Kiskút, Győrváros 3, Győrváros 4, Győrváros 2, Győrváros 1, and Győrváros 5.
- Blue:** Residential areas and surrounding districts. These include districts like Győrváros 6, Győrváros 7, Győrváros 8, Győrváros 9, Győrváros 10, Győrváros 11, Győrváros 12, Győrváros 13, Győrváros 14, Győrváros 15, Győrváros 16, Győrváros 17, Győrváros 18, Győrváros 19, Győrváros 20, Győrváros 21, Győrváros 22, Győrváros 23, Győrváros 24, Győrváros 25, Győrváros 26, Győrváros 27, Győrváros 28, Győrváros 29, Győrváros 30, Győrváros 31, Győrváros 32, Győrváros 33, Győrváros 34, Győrváros 35, Győrváros 36, Győrváros 37, Győrváros 38, Győrváros 39, Győrváros 40, Győrváros 41, Győrváros 42, Győrváros 43, Győrváros 44, Győrváros 45, Győrváros 46, Győrváros 47, Győrváros 48, Győrváros 49, Győrváros 50, Győrváros 51, Győrváros 52, Győrváros 53, Győrváros 54, Győrváros 55, Győrváros 56, Győrváros 57, Győrváros 58, Győrváros 59, Győrváros 60, Győrváros 61, Győrváros 62, Győrváros 63, Győrváros 64, Győrváros 65, Győrváros 66, Győrváros 67, Győrváros 68, Győrváros 69, Győrváros 70, Győrváros 71, Győrváros 72, Győrváros 73, Győrváros 74, Győrváros 75, Győrváros 76, Győrváros 77, Győrváros 78, Győrváros 79, Győrváros 80, Győrváros 81, Győrváros 82, Győrváros 83, Győrváros 84, Győrváros 85, Győrváros 86, Győrváros 87, Győrváros 88, Győrváros 89, Győrváros 90, Győrváros 91, Győrváros 92, Győrváros 93, Győrváros 94, Győrváros 95, Győrváros 96, Győrváros 97, Győrváros 98, Győrváros 99, Győrváros 100.
- Pink:** Peripheral areas. These include districts like Győrváros 101, Győrváros 102, Győrváros 103, Győrváros 104, Győrváros 105, Győrváros 106, Győrváros 107, Győrváros 108, Győrváros 109, Győrváros 110, Győrváros 111, Győrváros 112, Győrváros 113, Győrváros 114, Győrváros 115, Győrváros 116, Győrváros 117, Győrváros 118, Győrváros 119, Győrváros 120, Győrváros 121, Győrváros 122, Győrváros 123, Győrváros 124, Győrváros 125, Győrváros 126, Győrváros 127, Győrváros 128, Győrváros 129, Győrváros 130, Győrváros 131, Győrváros 132, Győrváros 133, Győrváros 134, Győrváros 135, Győrváros 136, Győrváros 137, Győrváros 138, Győrváros 139, Győrváros 140, Győrváros 141, Győrváros 142, Győrváros 143, Győrváros 144, Győrváros 145, Győrváros 146, Győrváros 147, Győrváros 148, Győrváros 149, Győrváros 150.

City Center and the Directly Connected Districts³

The city centre of Győr, with its historic buildings, dense urban fabric and tourist attraction, requires special attention. The city administration is seeking to reduce car traffic in the city centre by improving pedestrian and cycling infrastructure and increasing public transport options. It will also promote sustainability by renewing public spaces, increasing green areas and supporting local businesses. Nádorváros, Gyárváros and Révfalu districts are directly linked to the city centre, but contribute to the diversity of Győr with their own character. The urban development strategy gives priority to the rehabilitation of old industrial sites, especially in Gyárváros, where brownfield sites are being reused. Among the residential developments in Nádorváros and Révfalu, the focus will be on expanding community spaces and preserving green areas. Urbanisation and revitalisation of these

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neighbourhoods are important elements of the urban development strategy. In Újváros, priority will be given to social housing programmes and the development of community services, while in the Sziget, emphasis will be placed on waterfront development, recreation and nature conservation.

Residential Areas⁴

Residential areas are home to a significant part of Győr's population and sustainability challenges in these areas are particularly related to energy efficiency, transport infrastructure development and improving the quality of public spaces. The housing estates of Adyváros have become a model for energy-efficient building renovation and green space rehabilitation. The insulation of prefabricated buildings, the renovation of public spaces and the improvement of public transport links are all contributing to sustainability. The city government is working to minimise the environmental footprint of the estate while improving the quality of life for residents. Marcalváros's housing estates are also undergoing comprehensive energy efficiency programmes, with the active involvement of the residents' communities. In addition to increasing green areas and improving transport infrastructure, boosting community life is also key. The creation of community gardens and playgrounds in the neighbourhoods will also contribute to achieving sustainable urban development goals. The Jancsifalu residential area is a small but strategically important part of the city of Győr. Here, urban development efforts focus mainly on improving transport links, increasing energy efficiency and improving community infrastructure. Projects involving local residents will increase commitment to sustainability.

Peripheral Areas⁵

The peripheral areas are extensive, less urbanised areas of the city of Győr with a high potential for promoting sustainable development. These districts have significant green areas and agricultural potential, which the urban development strategy seeks to exploit.

Bácsa, Gyirmót and Györszentiván peripheral areas are Győr's agro-economic centres, where the promotion of sustainable agriculture and local food production (Palkovič, 2021) is an important part of the urban development strategy. The city government is working to ensure that these areas retain their rural character while supporting local farmers to adopt sustainable practices. In addition, improving transport links and developing local services are also a priority. The residential development of Kisbácsa, Kismegyer and Ménfőcsanak districts and the development of community infrastructure is a key challenge for urban development. The sustainable urban development strategy here focuses on improving transport links, creating community spaces and preserving local identity. In particular, it is important to preserve green spaces and use sustainable building practices. Pinnyéd, Sárás and Szabadhegy districts have both natural assets and development potential. Sustainability efforts here focus on nature conservation, water management and support for local communities. The city government seeks to preserve local ecosystems while promoting sustainable residential development.

⁴ The districts relevant to the analysis: Adyváros, Marcalváros I., Marcalváros II., Jancsifalu.

⁵ The districts relevant to the analysis: Bácsa, Gyirmót, Györszentiván, Kisbácsa, Kismegyer, Ménfőcsanak, Pinnyéd, Sárás, Szabadhegy.

RESULTS

Development Priorities for the City Centre and Related Neighbourhoods

Transport Improvement and Traffic Reduction

In the inner city and surrounding areas, residents place great emphasis on improving public transport. This includes starting new bus services and increasing the frequency of existing services. It is also important to promote alternative modes of transport such as cycling and walking, for example by creating cycle paths and pedestrian zones. The lack of parking spaces is a major problem for city centre residents. Therefore, the creation of parking garages and P+R car parks, as well as the redesign of the parking system in the city centre, are transport priorities.

Improving Green Spaces and Public Spaces

The inhabitants of the city centre and the surrounding neighbourhoods pay particular attention to the improvement of green spaces, parks and public spaces. The expansion of these areas, the launching of tree planting programmes and the regular maintenance of existing green spaces are essential to enhance the liveability of the city. The development of public spaces such as pedestrian streets, public parks and playgrounds is also an important objective. Residents demand new features to improve the quality of urban life, such as outdoor events, music pavilions and street furniture.

Expand Cultural and Social Services

There are a number of cultural institutions in the downtown areas that residents would like to see developed. For example, theatres, museums, art galleries, etc., whose expansion and modernisation would help to boost cultural life. Residents are calling for measures to care for the elderly and to develop social facilities, such as the creation or expansion of social centres, which would support the social cohesion of the city.

Improving Public Safety and Street Lighting

Improving public safety in the downtown and surrounding areas is a priority. Residents expect increased security in public spaces, for example by installing CCTV cameras, increasing police presence and supporting crime prevention programmes. Improving street lighting is also a priority, particularly in areas where additional lighting is needed to improve public safety and make night-time travel safer.

Development Priorities for Housing Estates

Infrastructure and Transport Development

Improving roads and parking facilities is a priority for people living in housing estates. This includes the upgrading of the internal road network, the creation of new parking spaces and the optimisation

of parking systems. For people living in housing estates, it is important to improve the availability and frequency of public transport, especially during peak periods, to facilitate access to the city centre.

Improving Public Spaces and Green Areas

Improvements to public spaces in residential areas include upgrading playgrounds, creating new community spaces and increasing recreational opportunities. Residents are calling for the modernisation of playgrounds, the creation of new sports fields and recreational facilities. Maintaining and expanding green spaces is also a priority, especially around housing estates where residents use these areas for recreation and leisure.

Improving Services and Public Safety

People living in housing estates often lack basic services such as shops, pharmacies and health facilities in the immediate vicinity. Local services could be expanded to make everyday life easier. In order to improve public safety in housing estates, there is a need to improve street lighting and increase police presence. These measures would increase residents' sense of security, especially in the evening and at night.

Improving Community Life and Social Services

For people living in housing estates, it is important to create and develop community spaces where they can organise a variety of programmes and events that foster community cohesion. Residents are calling for the expansion of social services for the elderly and vulnerable, such as new social centres or day care facilities to help meet the social needs of the local population.

Development Priorities for Peripheral Areas

Improving Transport Links

Facilitating access to the city centre is a priority for peripheral residents. This includes improving the road network, including widening roads, repairing potholes and building new roads to provide more efficient transport options. Public transport coverage in peripheral areas is often poor and residents are calling for an expansion of the public transport network, such as new bus services, more frequent timetables and better integration of existing services into the urban transport system.

Green Spaces and Environmental Sustainability

Preserving and enhancing green spaces, parks and forests in peripheral areas is key for residents. Maintaining these areas not only contributes to the preservation of local ecosystems, but also provides recreational opportunities for communities. Residents in peri-urban areas support sustainable solutions such as encouraging the use of renewable energy sources, increasing selective waste collection, and removing invasive plant species that can threaten local vegetation.

Develop Community and Recreational Facilities

New community centres, sports facilities, playgrounds and cultural centres are needed to boost community life in peripheral areas. These facilities will not only improve the quality of life for residents but also strengthen community cohesion. People living in peri-urban areas often lack basic services such as proximity to shops, pharmacies and doctors' surgeries. To increase their accessibility, expanding local services is also an important priority.

Improving Infrastructure and Public Safety

To improve public safety, street lighting needs to be improved, especially in more deserted streets and public spaces. Improved street lighting will help prevent crime and increase residents' sense of security. Ongoing maintenance of the road network, including regular renewal of roads and pavements, is also a priority for residents, especially in peripheral areas where road conditions are often below the urban average. These development priorities reflect the needs and aspirations of residents in each of these categories, the satisfaction of which can contribute to the sustainable development of the city as a whole and to improving the liveability of peripheral areas (Figure 2–4).

When examining the differences, the different needs and priorities of residents in different neighbourhoods should be taken into account. The three categories are summarised below to show where there was the greatest variation. The greatest divergence was therefore in the category of peripheral areas, where the specific needs of residents differ significantly from the priorities of the inner city and residential areas. This difference is most evident in transport links, green space management and public safety measures.

For those living in peri-urban areas, the biggest challenge is access to the city centre, which shows a significant difference compared to those living in the city centre and in housing estates. While traffic reduction and parking improvements are important for inner city residents, those living in peripheral areas tend to prioritise improving road infrastructure and increasing access to public transport.

For people living in peripheral areas, the preservation and enhancement of green spaces is of paramount importance, as these areas are directly linked to the natural environment. This is in contrast to the needs of inner city and residential areas, where the focus is more on the renovation of public spaces, parks and the development of new recreational facilities.

Residents of outlying areas often perceive a lack of public safety, particularly in less populated, more isolated areas. Improving street lighting and increasing public safety measures is therefore a higher priority than in the inner city, where police presence and street lighting are already at a relatively good level.



Figure 2. Transport Preferences by Neighbourhood

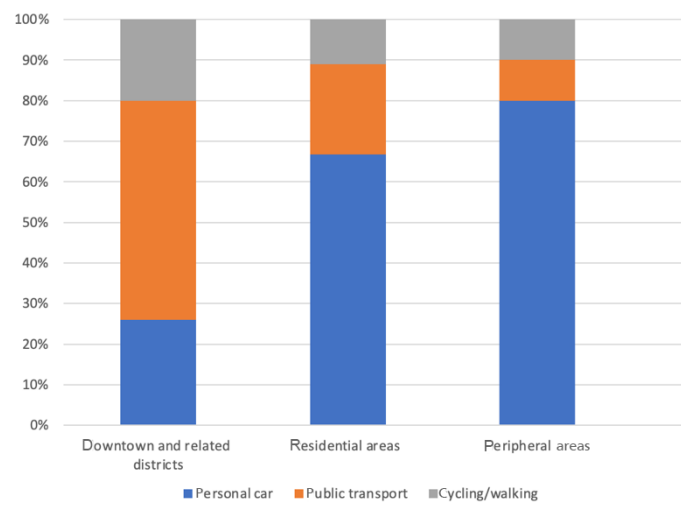


Figure 3. Satisfaction With Public Services by Neighbourhood

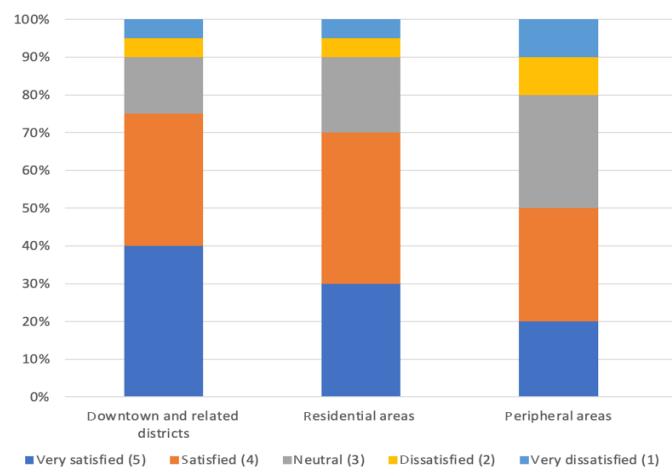
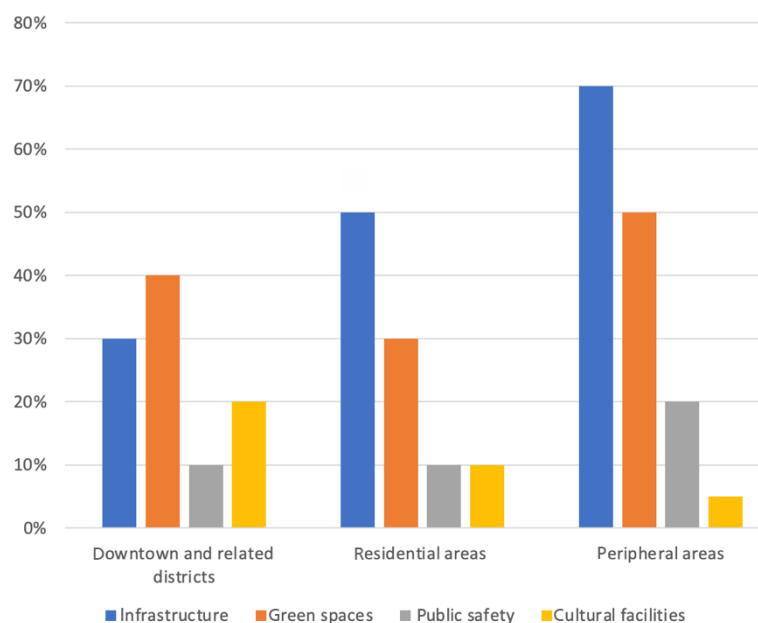


Figure 4. Development Priorities by Neighbourhood



CONCLUSIONS

The City of Győr's sustainable development strategy takes a multi-faceted and integrated approach to addressing environmental, economic and social challenges. Measures to create a green urban environment, improve transport facilities, water management and promote community participation all contribute to making Győr a liveable, sustainable city. In this way, the development of the city will ensure a green, healthy and liveable urban environment not only for its current residents but also for future generations. In the light of the above, an overall picture of the sustainability priorities of the city of Győr can be drawn as follows:

The issue of transport and energy efficiency (Kiss, 2017) has been highlighted in the Sustainable Urban Development Strategy of Győr. The European literature provides numerous examples (Tóth, 2018; Lechner Knowledge Centre 2020, Hungarian Central Statistical Office, 2021) of how the development of sustainable transport systems can contribute to improving urban quality of life and reducing environmental pressures (Institute for Transport Research, 2019). Pucher and Buehler (2012) provide a comprehensive study on how the development of cycling infrastructure, pedestrianisation and the integration of public transport systems contribute to the sustainability of cities (Magyar, 2015).

In the city of Győr, special attention (Hungarian Urban Society, 2019) has been paid to the promotion of cycling and walking, which is to be implemented by adopting European good practices. In addition, investments in energy efficiency, such as the energy modernisation of public and residential buildings, also contribute to achieving sustainability goals.

The expansion of green spaces and the development of community spaces (Hungarian Urban Society, 2019) are also important elements of a sustainable urban development strategy. Since the work of Jacobs (1961), we know that urban green spaces (Schmeller, 2021) and community spaces (Kondor, 2016) play a key role in improving the quality of life of urban residents. In Győr, the city government has set the goal of preserving existing green spaces and creating new parks and community spaces (Government of Hungary, 2018) that will help to revitalise community life and preserve urban ecosystems.

In the urban development strategy, special attention has been paid to involving local residents in the development of green spaces, partly through questionnaire surveys (Németh, 2020; Kovács, 2017).

In planning the sustainable urban development strategy of the city of Győr, the city administration has paid special attention to involving the population and taking their opinions into account. The different needs and priorities of the people living in different parts of the city have contributed significantly to the development of the strategy. The following summary of this paper presents the transport preferences, satisfaction with public services and development priorities of the population, grouped by neighbourhood category (downtown and related neighbourhoods, residential areas, peripheral areas).

The preferences, satisfaction and development priorities of the population of Győr by neighbourhood show significant differences, reflecting the specificities and needs of the neighbourhoods. For the city administration, this information provides an important basis for the targeted and effective design of

a sustainable urban development strategy that takes into account the different expectations and needs of different population groups.

The example of Győr demonstrates that adapting sustainability principles locally—such as expanding green spaces, enhancing public areas, and improving the energy efficiency of transport systems—can effectively contribute to a higher quality of urban life while supporting global sustainability objectives. Strong cooperation between local governments and communities strengthens the legitimacy of sustainability programs, increases public acceptance, and enhances the long-term effectiveness of urban development initiatives. The adoption of new technologies, green infrastructure, and alternative transport solutions enables cities to better address the challenges of climate change and rapid urbanization.

Compact, walkable, transit-oriented, and mixed-use urban designs contribute to lower carbon emissions, stronger community cohesion, and more efficient resource use. Integrating economic, social, and environmental considerations into planning and evaluation is essential to achieve sustainable urbanization. Cities must continuously measure their progress using complex indicators to fully understand the impacts of their development efforts. Although each city faces unique challenges, successful local strategies, such as Győr's sustainability efforts, can serve as inspiration and models for other cities seeking their own paths toward sustainable development.

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Sustainable Management of Urban Nature Reserves: Insights from Visitors' Travel Behaviours and Motivations at Rietvlei Nature Reserve

ABSTRACT

As the world continues to urbanize, increasing pressure is being placed on natural spaces, which are crucial for providing both residents and visitors with opportunities for nature experiences amidst „concrete jungles.” This research is centred in Tshwane, South Africa, with a specific focus on the Rietvlei Nature Reserve (RNR). The goal was to gather data regarding visitors' travel patterns to, and motivations for visiting, RNR. A structured questionnaire was designed and distributed to RNR visitors using a convenience sampling technique. The data presented, together with the ensuing discussion, is based on responses from RNR visitors (n = 129) concerning their travel patterns and motivations. The findings show that RNR experiences a high number of repeat visits and short stays, primarily from group visitors who mostly engage in adventure and health-related activities. Recommendations include improving infrastructure at RNR to better support group activities and to promote the associated health benefits. In addition, suggestions were made to increase awareness of the reserve's role in environmental conservation. This research underscores the significance of natural spaces in urban areas, highlights their value for health and well-being, and emphasizes the necessity of protecting these environments through sustainable management.

Keywords: Rietvlei Nature Reserve, urban nature reserves, travel patterns, visitor motivations, sustainable management

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INTRODUCTION

Modern cities globally are increasingly being shaped by urbanization and growing populations concentrated in metropolitan regions. A notable challenge of this growth is the degradation of the natural landscape, resulting in a decline in urban green spaces that are vital for the well-being of both city dwellers and visitors alike (Borgström et al., 2012). Among the many benefits these green spaces provide are opportunities for outdoor and adventure activities, recreation and relaxation, as well as support for physical and mental well-being (Beckline & Yujun, 2014).

This highlights the need to explore how visitors to these natural environments make use of such spaces—especially in urban nature reserves, where human interactions are significant for maintaining both public health and ecological well-being. Despite the growing importance of urban nature reserves, research gaps remain in understanding the specific travel patterns and motivations of visitors to these areas, particularly in developing countries such as South Africa. Most research on nature reserves focuses on remote locations, leading to limited knowledge about how people interact with nature within city limits (De Jager, 2023a). Moreover, there is little research on how specific visitor groups—such as those seeking health and recreational benefits—affect the management and sustainability of these natural spaces.

The Rietvlei Nature Reserve (RNR) in Tshwane, South Africa, is one of the most significant natural resources within an urban environment in the country, offering visitors accessible opportunities to connect with nature (Mapuru et al., 2021). RNR plays an important role in the environmental and social fabric of Tshwane (Mapuru et al., 2021). It is home to rich biodiversity and a variety of recreational opportunities. However, research on how visitors engage with the reserve's natural environment remains limited (Haussmann et al., 2022). This gap hinders the reserve's management from optimizing visitor experiences and promoting sustainable management strategies (Mapuru et al., 2021).

This study, therefore, aims to address this gap by exploring the travel patterns and motivations of RNR visitors. It seeks to gain insights into the key factors influencing visitation, with a view to offering valuable recommendations for the sustainable management of urban nature reserves, while supporting the health and recreational needs of both visitors and urban residents.

Research into the travel patterns and motives of RNR visitors is essential for understanding the relationship between urban populations and natural resources. Urban green spaces provide a refuge for residents and visitors in increasingly overpopulated, congested, and industrialized cities (Wasilewski et al., 2019; Kiss et al., 2025). These areas serve as centers for relaxation, recreation, and environmental education (De Jager, 2023a).

Understanding the motivational factors and travel patterns related to RNR offers valuable insights into how people engage with nature in a metropolitan context. This study is particularly important for informing urban planning and emphasizing the role of natural spaces in fostering environmental stewardship and promoting sustainable tourism within urban areas. Furthermore, as South Africa faces growing urbanization and biodiversity loss, insights into travel patterns and motivations related to urban nature reserves can help guide policy development aimed at conserving natural resources

and ensuring equitable access to green spaces among all stakeholders. Such research deepens our understanding of human–environment interactions and simultaneously supports the sustainable management of urban landscapes.

LITERATURE REVIEW

In today's world of rapidly growing populations, cities are increasingly characterized by concrete landscapes, with natural spaces confined to fragmented green patches scattered across metropolitan areas (Borgström et al., 2012). These green spaces are recognized as essential for promoting environmental conservation and public health in urban settings (Beckline & Yujun, 2014). According to Wasilewski et al. (2019), urbanization is a defining global trend, with more than half of the world's population now residing in urban areas. While cities serve as economic hubs, cultural centers, and spaces for innovation, they are also experiencing significant environmental degradation, biodiversity loss, and a decline in the quality of life for urban dwellers (Kato & Matsuba, 2021).

In this context, urban green spaces are undoubtedly crucial for mitigating many of these challenges. They offer a range of social and health benefits, including the provision of clean air and opportunities for mental health support, relaxation, and recreation (Wasilewski et al., 2019). Furthermore, these spaces contribute to the preservation of urban biodiversity by providing habitats for wildlife and supporting natural ecosystems. They also serve as ecological corridors that connect fragmented landscapes (Pell & Tidemann, 1997; Kato & Matsuba, 2021).

Urban natural areas—particularly nature reserves—are relatively undisturbed environments preserved within city limits that provide access to natural experiences (Hermann & Du Plessis, 2014). These reserves play a key role in both ecological preservation and the physical and psychological well-being of urban residents and visitors alike (Schnetler et al., 2021).

To ensure the sustainability of these spaces, it is critical to understand how visitors interact with them and what motivates their visits (Wasilewski et al., 2019). Travel patterns provide insight into how visitors use these areas and what experiences they seek (Wasilewski et al., 2019). Similarly, understanding visitor motivations can guide more effective management strategies that both meet the needs of users and promote sustainability (Seeland et al., 2002). Although motivations vary, common reasons for visiting nature reserves include recreation, relaxation, and physical and mental health benefits (Wasilewski et al., 2019; Hung & Chang, 2022). Visitors often engage in activities such as birdwatching, hiking, cycling, or jogging (Mapuru et al., 2021; Haussmann et al., 2022).

Nature reserves are known for their therapeutic effects, with many visitors seeking out nature to reduce stress and enhance well-being (Wasilewski et al., 2019). In urban contexts, nature reserves are often viewed as sanctuaries from the pressures of city life (Yang et al., 2021). Some visitors are also motivated by a desire for adventure and outdoor activities (Smith & Somers, 2025). Urban nature reserves provide unique opportunities for such activities, which may be difficult to access elsewhere in the city. These include game viewing, trekking, horseback riding, quad biking, and environmental

education programs. Additionally, there is a growing interest in environmental conservation and sustainable tourism among nature reserve visitors.

Despite these positive aspects, managing nature reserves in urban areas comes with several challenges. One key issue is balancing the conservation of natural resources with the demands of visitors (Liu et al., 2022; Gonda & Rátz, 2024). Common problems include overcrowding, overuse of natural resources, and environmental degradation, all of which negatively impact the ecosystems within the reserves (De Jager, 2023b). Some reserves are also home to endangered species, which face heightened risks if environmental impacts are not properly managed (Toxopeus & Polzin, 2021; Gonda & Rátz, 2024).

These challenges underscore the urgent need for sustainable management practices that accommodate visitors' needs without compromising the ecological integrity of the reserves (Miller et al., 2023). Sustainable management is essential for conserving biodiversity and enhancing the health and well-being of urban populations. By understanding visitor motivations and travel patterns, reserve managers can develop strategies that promote a balanced relationship between human activity and environmental conservation.

METHODS

Spatial scope of the analysis

Rietvlei Nature Reserve is a provincial nature reserve owned by the City of Tshwane Metropolitan Municipality and is located near several urban centers. The area was acquired in 1929 by the local government to expand the city's water-provisioning capacity in order to supply drinking water to the growing population of Tshwane (Marais, 2004; Jamison et al., 2016; De Jager, 2020).

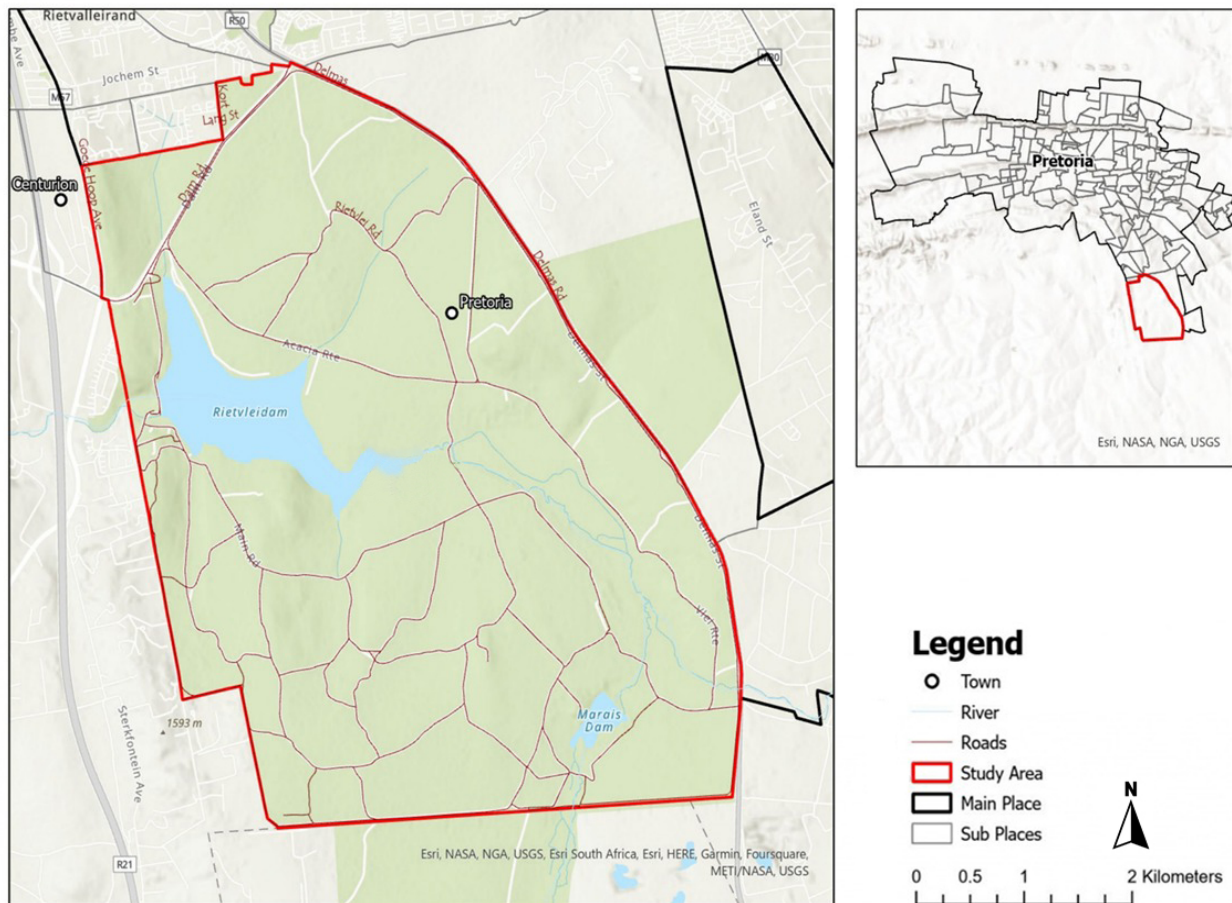
Figure 1. Rietvlei Dam



Source: Authors

The reserve covers an area of approximately 4,000 hectares and encompasses the Rietvlei Dam (Figure 1) (Marais, 2004; De Jager, 2020; De Jager, 2023b). It is located southeast of the City of Tshwane, in the Gauteng Province of South Africa (Marais, 2004; De Jager, 2020). Figure 2 shows the map of the Rietvlei Nature Reserve.

Figure 2. The study area within Pretoria



Source: Rietvlei Nature Reserve

The plant composition of the area consists of open grassland interspersed with small clusters of indigenous trees found throughout the reserve. The vegetation is classified as Rand Highveld Grassland (Marais, 2004; Jamison et al., 2016). The reserve is home to a wide range of bird species, including large birds such as the ostrich, and approximately 350 bird species have been recorded in the area (Marais, 2004). Large mammals also inhabit the reserve, including red hartebeest, Burchell's zebra, black wildebeest, blesbok, cheetah, waterbuck, buffalo, and white rhinoceros (Marais, 2004; De Jager, 2020). The RNR offers a variety of activities, including birdwatching, game drives, and hiking trails (Marais, 2004; De Jager, 2020). In addition, the reserve provides picnic areas and braai facilities for visitors. Figure 3 illustrates one of the available activities, namely game drives, within the RNR.

Figure 3. Game drives in RNR



Source: Authors

The Rietvlei Nature Reserve serves as an ideal case study for researching the sustainable management of urban nature reserves, offering a unique opportunity to assess visitors' travel patterns and motivations within an urban context. Its diverse ecosystems, combined with its accessibility to local populations, make it a key site for examining how visitor behavior influences conservation efforts. By exploring how the reserve attracts and engages with visitors, the study provides valuable insights into balancing conservation goals with public needs and expectations. To this end, the methods used to collect data in this research area are presented below.

Survey methodology

In this quantitative study, a structured questionnaire was developed and distributed to visitors of the Rietvlei Nature Reserve (RNR). A convenience sampling technique was employed to select the respondents. The data presented in this research—along with the accompanying discussions and recommendations—are based on the responses of RNR visitors ($n = 129$) regarding their travel patterns and motivations for visiting the reserve. Respondents were asked to rate their motivations for visiting RNR using a five-point Likert scale, where 1 indicated "extremely unimportant" and 5 indicated „extremely important." Table 4 presents these motivations, ranked from the lowest to the highest based on their perceived importance. Table 1 displays the age and gender distribution of the research respondents.

Two key questions were included in the structured questionnaire to address the research objective: (1) information related to travel patterns, and (2) information concerning the motivations for visiting the RNR. The results obtained are discussed in the following section.

Table 1. Age and gender of the respondents

Variables	Frequencies	Percentage
<i>Age</i>		
18 –30 years	32	24.8%
31–40 years	20	15.5%
41–50 years	20	15.5%
51–60 years	38	29.5%
61–70 years	16	12.4%
71–80 years	3	2.3%
<i>Gender</i>		
Male	62	48.1%
Female	67	51.9%

RESULTS

Travel patterns to Rietvlei Nature Reserve

The results show that the RNR frequently receives group visits, which are predominantly short-term in nature. Table 2 presents the findings related to the frequency of visits to the RNR, the length of stay, and group composition.

Table 2. Travel frequency to the RNR

Variables	Frequency	Percentage
<i>Have you visited the Rietvlei Nature Reserve before?</i>		
Yes	80	62.0%
No	49	38.0%
<i>If yes, how many times have you visited the Rietvlei Nature Reserve in the past year?</i>		
Once	18	14.0%
Two times	9	7.0%
Three times	8	6.2%
Four times	9	7.0%
More than five times	35	27.0%
Have not visited the reserve before	50	38.8%
<i>Are you travelling with other people?</i>		
Yes	110	85.3%
No	19	14.7%
<i>If yes, how many people are you travelling with in your group including yourself?</i>		
Two people	60	46.5%
Three people	28	21.7%
More than four people	22	17.1%
Traveling alone	19	14.7%
<i>How long is your stay at the Rietvlei Nature Reserve?</i>		
One day	127	98.4%
More than two days	2	1.6%

This study found that most visitors to the Rietvlei Nature Reserve had visited the destination previously, indicating a high level of repeat visitation. These findings suggest that the reserve enjoys a significant number of loyal visitors. Regarding the duration of visits, compared to national parks, visitors to the Rietvlei Nature Reserve tend to spend shorter periods at the site. The results show that most RNR visitors stay for a single day during each visit, whereas visitors to national parks generally

stay for longer durations. Respondents were also asked to identify the key pull factors influencing their decision to visit the reserve (Table 3).

Table 3. Pull factors to the RNR

Variables	Frequency	Percentage
<i>The nature reserve facilities</i>		
Yes	36	27.9%
No	93	72.1%
<i>Wildlife and birds</i>		
Yes	121	93.8%
No	8	6.2%
<i>The nature reserve landscape</i>		
Yes	73	56.6%
No	56	43.4%
<i>The Rietvlei Dam</i>		
Yes	61	47.3%
No	68	52.7%
<i>Adventure activities</i>		
Yes	19	14.7%
No	110	85.3%

The results indicate a strong interest in the natural landscape of the reserve, as well as in the viewing of wildlife and bird species, which emerge as key pull factors for visiting the RNR. In terms of tourist attractions, the study found that visitors are particularly drawn to the wildlife and birdlife present in the area, the Rietvlei Dam, and the surrounding natural scenery. The findings regarding the motivations to visit the reserve are presented below.

Motivation factors for visiting the RNR

The Principal Axis Factoring extraction method was used to develop a pattern matrix, applying the Oblimin rotation method. Both Bartlett's Test of Sphericity and the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy were examined. Bartlett's Test yielded p-values < 0.001, indicating that the correlation structure was suitable for factor analysis. Four motivational factors were identified, collectively accounting for 55% of the total variance. The factors demonstrated strong internal consistency, with reliability coefficients ranging from 0.7 to 0.8. The KMO value was 0.811, confirming sampling adequacy (Field, 2009; Pallant, 2013; Hermann et al., 2016). To assess the reliability of the data, Cronbach's Alpha test was conducted, yielding a score of 0.877. According to Tan (2009), a Cronbach's Alpha of 0.8 or above indicates high reliability. The main motivational factors for visiting RNR are outlined in Table 4 (Pattern Matrix) and Table 5 (Factor Correlation Matrix).

Factor 1: Experience nature

This factor received the second-highest mean score (3.62) and includes motivations such as learning about animals and plants, seeing flora and fauna, and connecting with nature. It was identified as a key motivational factor for visiting RNR and has also been reported in previous studies focused on national parks (Kruger & Saayman, 2010; Hermann et al., 2016; Van der Merwe et al., 2021).

Factor 2: Escape and relaxation

This factor obtained the highest mean score (4.06) and encompasses themes such as escaping daily routines, spending time with family and friends, and seeking relaxation. It has consistently been identified as a critical motivator in numerous studies on national park visitation (Kruger & Saayman, 2010; Hermann et al., 2016; Muzeza et al., 2018; Van der Merwe et al., 2021). In this study, it emerged as the primary motivation for visiting the RNR.

Factor 3: Participation in activities

This factor had the lowest mean score (2.20) and includes motivations such as horse riding, game drives, attending events, hiking, and fishing. It has been identified in prior research as a relevant but less dominant motivational factor (Kruger & Saayman, 2010; Hermann et al., 2016; Muzeza et al., 2018; Van der Merwe et al., 2021).

Factor 4: Personal benefit

This factor includes motivations related to improving one's health, gaining value for money, and seeking spiritual experiences. It received a mean score of 3.20 and has also been identified in previous studies (Kruger & Saayman, 2010; Hermann et al., 2016; Muzeza et al., 2018).

The results of the factor correlation matrix indicate a very low correlation between the four identified factors, suggesting that they represent relatively distinct and well-defined motivators. This study focused on the sustainable management of urban nature reserves, with a particular emphasis on the Rietvlei Nature Reserve (RNR) in Tshwane, South Africa. The primary aim was to understand the travel patterns and motivations of visitors to the reserve. Findings regarding travel patterns reveal a high level of repeat visitation to RNR, primarily by group visitors. Moreover, there is clear evidence of short-duration visits, especially single-day trips.

The key motivations for visiting RNR were identified as escape and relaxation, along with experiencing nature. These findings highlight the multifaceted nature of visitor engagement with the reserve. While lower-ranked motivations included environmental education and general nature-based experiences, factors related to personal well-being—particularly health benefits, spiritual enrichment, and perceived value for money (VFM)—emerged as significant drivers of visitation.

These results align with broader trends that show frequent visits are often associated with physical and mental wellness activities, typically undertaken in group settings. Additionally, the findings underscore the reserve's role as a valuable communal space, as indicated by the mid-level importance assigned to social and recreational motivations.

The diverse range of motivational factors identified at RNR highlights the need for a management approach that not only prioritizes ecological conservation but also supports health, social interaction, and accessibility. Such a strategy is essential for ensuring the long-term sustainability of the reserve. Furthermore, the findings affirm the broader significance of urban nature reserves as spaces that simultaneously offer opportunities for recreation, relaxation, and environmental stewardship. In this respect, the study extends previous research on nature-based tourism in South Africa and similar

destinations by providing new insights into how urban nature reserves can deliver meaningful visitor experiences while supporting sustainable management practices.

Table 4. Pattern Matrix

Motivations	Factor			
	Experience nature	Escape and relaxation	Participate in activities.	Personal benefit.
Mean Values	3.62	4.06	2.20	3.20
To learn about animals	.850			
To learn about endangered species	.845			
To learn about plants	.791			
To learn about conservation	.699			
To see plants	.632			
To learn about the history of the nature reserve	.606			
To connect with nature	.439			
To see animals	.408			
To get away from my daily routine		.759		
To spend time with family and friends		.678		
To relax		.654		
Horse riding			.830	
Fishing			.636	
To attend an event			.621	
Game drives			.565	
Hiking trails			.448	
To improve my health				-.685
It is value for money				-.616
For spiritual experience				-.470

Table 5. Factor Correlation Matrix

Factor	Experience nature	Escape and relaxation	Participate in activities	Personal benefit.
Experience nature	1.000	0.163	0.322	-0.295
Escape and relaxation	0.163	1.000	-0.022	-0.256
Participate in activities	0.322	-0.022	1.000	-0.139
Personal benefit.	-0.295	-0.256	-0.139	1.000

The findings of this study suggest that understanding visitors' travel patterns and motivations is essential for the effective and sustainable planning and development of urban nature reserves such as the Rietvlei Nature Reserve (RNR). For instance, the identification of primary motivations—such as experiencing nature and seeking relaxation—can assist reserve managers in tailoring offerings to meet these needs, thereby enhancing visitor satisfaction and encouraging repeat visits.

Moreover, the results underscore the significant role that nature reserves play in promoting health and well-being among urban populations. These spaces offer a crucial balance between built and natural environments, a benefit that becomes increasingly important in the context of rapid urbanization, where natural areas are under growing pressure. Ensuring their protection and sustainable use is vital for the long-term well-being of both residents and visitors.

The study also highlights the importance of addressing the diverse needs of visitors when developing management strategies for urban nature reserves. Designing programs and experiences that align with

various motivational factors can help create a more inclusive and engaging environment. For example, offering guided adventure tours, wellness activities such as outdoor yoga sessions, or educational initiatives focused on biodiversity can not only enrich the visitor experience but also foster deeper emotional and intellectual connections with nature. By accommodating a wide range of interests, reserve managers can support sustainable engagement while promoting conservation goals.

Furthermore, the high prevalence of short stays—particularly one-day visits—emphasizes the need for effective crowd management and optimal resource allocation within the reserve. A high turnover of visitors in a limited time can strain infrastructure and threaten ecosystem health. By analyzing visitor patterns, managers can better prepare for peak periods, ensuring the reserve is equipped to accommodate large crowds without compromising its ecological integrity. Essential measures include clear signage, well-maintained pathways, and efficient waste management systems. Promoting responsible visitor behavior through sustainable tourism practices is critical to preserving the environmental quality of urban nature reserves.

The role of urban nature reserves such as Rietvlei is becoming increasingly critical in the face of rapid urbanization, where green spaces are frequently threatened by expansion and development. As cities continue to grow, preserving natural areas becomes essential not only for environmental conservation but also for the well-being of urban populations. This research emphasizes the therapeutic value of nature reserves, particularly in urban contexts where access to nature is limited. By promoting the health benefits associated with spending time in natural environments, urban reserves can be positioned as vital components of urban infrastructure.

To ensure the preservation, accessibility, and effective management of these spaces, collaboration between local governments, conservationists, and communities is essential. Long-term sustainability will depend on fostering partnerships that prioritize both ecological conservation and community engagement, ensuring that urban nature reserves continue to function as spaces for relaxation, recreation, and environmental stewardship.

This research also has practical implications for the management of urban nature reserves. Given that group visits to RNR are common, there is a need to enhance infrastructure that supports group-based activities. This could include developing spaces for environmental education, group gatherings, and outdoor recreation. Such initiatives can help attract a broader visitor base and foster social interaction. Additionally, given the established link between nature-based activities and health, the reserve is encouraged to promote wellness-focused offerings. These might include fitness programs, more challenging hiking trails, and designated quiet zones for visitors seeking meditation and relaxation. Such offerings would enhance the reserve's appeal by supporting the physical and mental well-being of visitors.

Furthermore, it is essential to implement awareness programmes focused on environmental protection and biodiversity conservation. Educating visitors on the ecological significance of the reserve can foster a more responsible and sustainable interaction with the natural environment. Marketing strategies should also be aligned to position RNR as a sanctuary for urban residents seeking tranquility and nature-based experiences, emphasizing its scenic beauty and peaceful atmosphere.

For South Africa to fully realize the potential and significance of urban nature reserves, coordinated national efforts are required to integrate these spaces into broader urban development and public health frameworks. Government agencies such as SANParks, the Department of Forestry, Fisheries and the Environment (DFFE), and local municipalities should take the lead in establishing a unified framework for the protection, funding, and promotion of urban green spaces. Moreover, robust collaboration with academic institutions, the private sector, and non-governmental organizations (NGOs) is crucial to foster innovation, community involvement, and long-term sustainability. Comparable international destinations may also benefit from adopting similar models to ensure that nature reserves contribute meaningfully to urban well-being, climate resilience, and equitable access.

Finally, this study provides a foundation for future research into the socio-economic and environmental impacts of developing urban nature reserves. Comparative studies between urban reserves and national parks could offer valuable insights into the unique challenges and opportunities associated with each. Additionally, further exploration into the sociocultural factors influencing visitor travel patterns and motivations could support the development of more inclusive management strategies aimed at attracting diverse user groups. Investigating the role of sustainable practices and their effect on visitor satisfaction and behavior could also yield important insights for the effective stewardship of urban natural spaces for future generations.

CONCLUSIONS

This research contributes to the understanding of visitor travel patterns and motivations related to urban nature reserves, while also offering important implications for their sustainable management. By emphasizing visitor satisfaction and enhancing the role of Rietvlei Nature Reserve (RNR) in promoting nature experiences, health, relaxation, and environmental conservation, the reserve can continue to flourish as a vital urban green space.

The study highlights the crucial importance of such spaces in fostering health and well-being, underscoring the ongoing need for concerted efforts to protect and sustainably manage these essential natural resources. The insights gained from the RNR case study provide practical and valuable guidance on the evolving role of urban green spaces—particularly urban nature reserves—in addressing the diverse needs of both residents and visitors in urban environments.

As global urbanization accelerates, this research reinforces the imperative to prioritize the development and management of green spaces as stewards of biodiversity, while simultaneously serving as critical venues for education, health and wellness, recreation, and community cohesion. The long-term planning and management of these areas require robust, evidence-based strategies that are responsive to visitor motivations and ensure the preservation of ecological integrity.

Ultimately, the RNR case exemplifies the growing significance of urban green spaces within the fabric of urban geography—where the dynamic interplay among ecology, human behavior, and spatial planning shapes urban quality of life, supports sustainable livelihoods, and facilitates the long-term development of resilient, sustainable cities in an era of rapid urban growth.

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Gashi, Nazim¹

Morphometric Analysis of the Catchment of the Leshan River, Kosovo

ABSTRACT

This study examines the hydromorphological characteristics of the Leshan River Basin in southern Kosovo, selected for its diverse topographic and hydrological features. As the largest tributary of the Toplluha River, the basin displays steep gradients in the east and gentle slopes in the west, influencing runoff distribution and erosion potential. Utilizing Geographic Information Systems (GIS), Remote Sensing (RS), Digital Elevation Models (DEMs), and Unmanned Aerial Vehicle (UAV) imagery, the study quantifies the basin's physical and hydrological attributes. Over twenty-five morphometric parameters were calculated and grouped into areal, linear, and relief categories. The Leshan River system reaches up to the fifth stream order, with a mean bifurcation ratio of 3.07 and a drainage density of 1.67 km/km², reflecting a moderate balance between infiltration and runoff. The low elongation ratio (0.45) and high relief (1,396 m) indicate a structurally controlled, high-energy fluvial environment. Seasonal flow variability—driven by snowmelt and rainfall—and the strong correlation between groundwater levels and terrain elevation underscore the dynamic interaction between surface and subsurface hydrology. These findings provide a spatially grounded understanding of watershed behavior and support more targeted water management strategies in similar mountainous and tectonically active regions.

Keywords: morphometric analysis, Leshan River, drainage basin, groundwater-elevation correlation, Kosovo

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INTRODUCTION

The Leshan River has not been exclusively studied; however, when considered as part of the broader Toplluha Basin, several relevant investigations have been conducted. Within the Leshan River itself, various studies have explored specific fields, including geology, hydrology, hydrogeology, and biogeography. The earliest research dates back to the 19th century, with authors such as Žujović (1893, 1900) providing general geological insights into the region. Detailed examinations of surface mineralization in the basin were carried out by the Institute of Geological and Geophysical Research in Belgrade. These efforts intensified significantly after World War II.

The Institute for Hydroeconomics “Jaroslav Černi” in Belgrade played a pivotal role in studying water resources across Kosovo. Their findings were published in the *Atlas of Maps* in 1981 (Jaroslav Černi). Regarding river flow regimes in Kosovo, the *Bulletin of the Serbian Geographical Society* featured works by Živković and Gavrilović (2009), specifically addressing seasonal flow variations and hydrological dynamics of Kosovo’s rivers, with the Leshan River presented as a concrete case.

Pllana (1996) calculated the water resources in Kosovo’s main basins, including per capita water availability. Additionally, Bytyqi (2006) analysed the hydrological characteristics of the Toplluha Basin (University of Prishtina, 2006), giving particular attention to the Leshan River among its tributaries.

Furthermore, in relation to the water resources of the Toplluha Basin, the study *Water Resources in the Basin of Drini i Bardhë, Kosovo* by Avdullahi et al. (2008), presented at the BALWOIS Conference in Ohrid, addressed water-related issues across the major tributaries of the White Drin River. Early biogeographical studies also contributed valuable insights. Notably, in 1986, due to its natural beauty and botanical reserves, a portion of this area was declared part of a National Park within the Sharr Mountains (Kosovo Environmental Protection Agency, 2021). This comprehensive overview of the Leshan River contributes to our understanding of water resources and hydrological dynamics in this vital region.

A mathematical and quantitative analysis of the Earth’s surface configuration, including the size and shape of its landforms, is known as morphometric characterization (Shekhar, 2022; Agarwal, 1998). As a quantitative method of analysing drainage basins, morphometric analysis reveals characteristics of drainage patterns and the evolution of surface runoff, groundwater infiltration capacity, groundwater potential, groundwater levels, and more (Nikhil, 2012). These approaches support the morphometric investigation of the Leshan River Basin.

The aim of this research is to conduct a comprehensive analysis of the physical-geographical characteristics of the Leshan River Basin, with particular emphasis on hydrological and geomorphological features. Conducting a systematic analysis is essential for understanding catchment configuration, which encompasses relief, linear, and areal aspects. Linear parameters include stream length, number of streams, bifurcation ratio, mean stream length ratio, stream frequency, drainage density, drainage texture, drainage intensity, length of overland flow, and the RHO coefficient. Relief characteristics include watershed relief, relief ratio, relative relief, ruggedness number, and the elevation range between the highest and lowest points. Areal parameters cover circulatory ratio, watershed area, perimeter, form factor ratio, basin length, elongation ratio, lemniscate ratio, and

compactness coefficient. In this study, the most relevant quantitative morphometric characteristics were identified and applied.

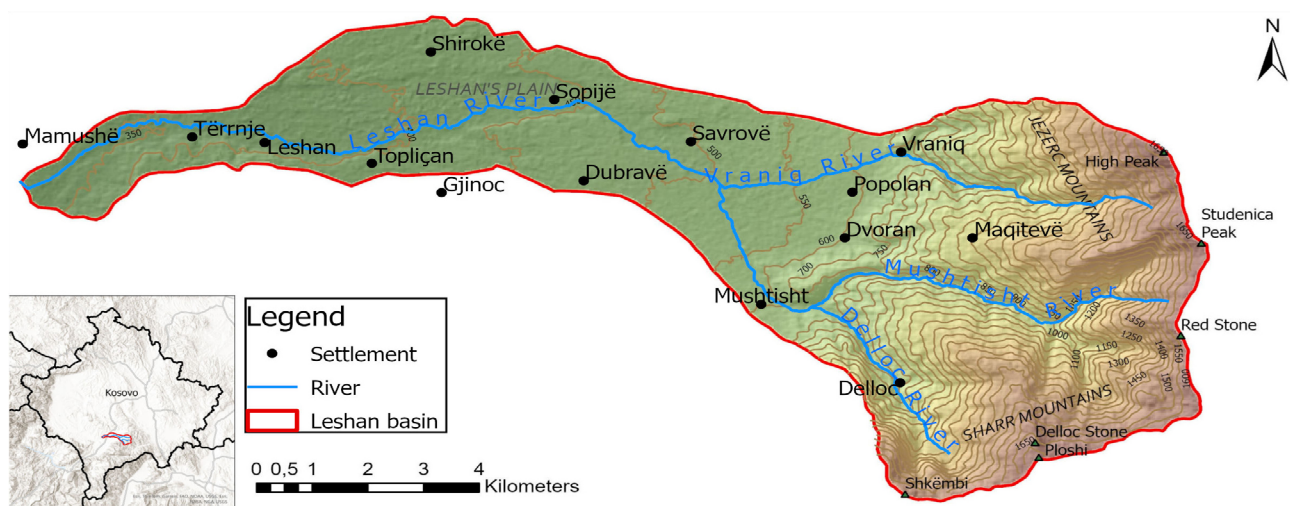
By thoroughly examining these parameters, the study aims to enhance understanding of the current state of the Leshan River Basin and its environmental dynamics. The findings contribute to more effective management and conservation of the basin while laying the groundwork for future research on sustainable resource management. Studying drainage basin processes helps clarify water flow and its interactions within the hydrological cycle, offering valuable insights for water management and resource planning.

METHODS

Spatial and environmental context of the study area

The Leshan River Basin, located in southern Kosovo (Figure 1), covers an area of 80.7 km² and contributes 16% to the Toplluha River system, making it the largest tributary in the region. The river originates from the confluence of its two main tributaries, the Vraniq and Mushtisht rivers, whose sources lie at elevations above 1,700 meters in the Sharr Mountains. The basin's lowest point is at the river mouth near Mamushë, at 327 meters above sea level, while the highest point is Studenica Peak, reaching 1,723 meters above sea level (Figure 4).

Figure 1. The watershed of the Leshan River

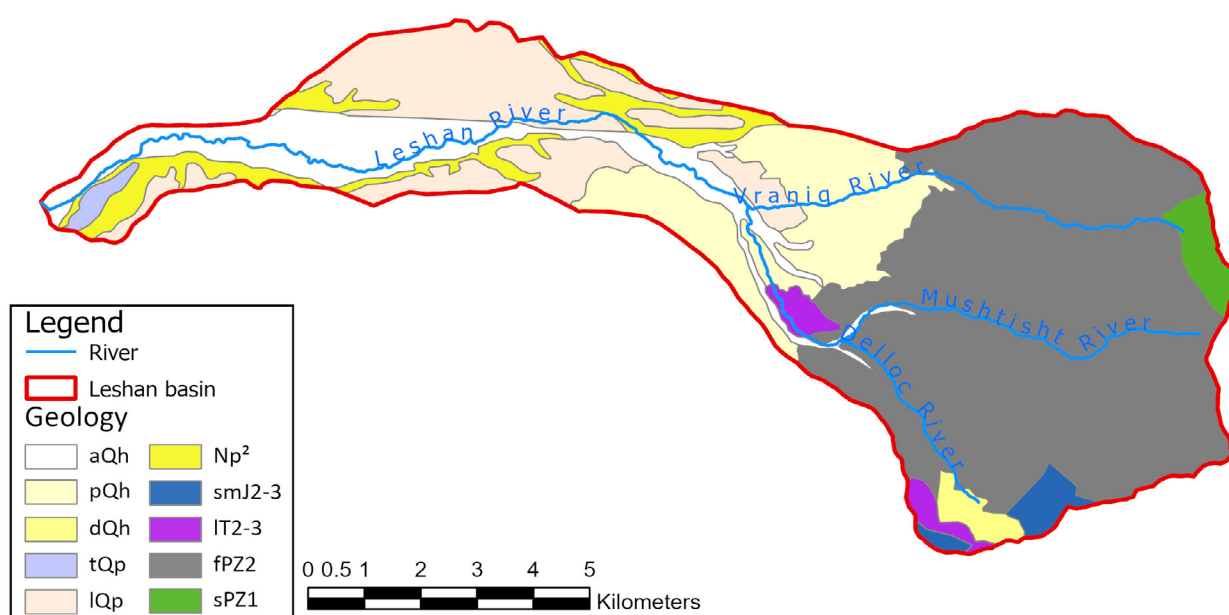


The Leshan River Basin spans two geotectonic zones: the Sharr–Korab Tectonic Zone (SKZ), which covers the eastern mountainous and plain areas, and the Ophiolitic Zone (OB) in the west (Tectonic Map of Kosovo, 2006). The basin's geology includes rock formations ranging from the Palaeozoic to the Cenozoic, which significantly influence its hydrological and geomorphological processes.

Palaeozoic formations dominate the eastern part of the basin and consist primarily of schists and meta-sandstones, particularly around Studenica Peak (1,723 m). Triassic and Jurassic rocks are present in the southern highlands, represented by limestone, dolomite, and volcanic material, all of which

contribute to the structural complexity and erosion dynamics of the area. In the western lowlands, Cenozoic sediments (from the Pliocene to the Holocene), such as gravel, clay, and alluvium, shape the drainage characteristics and groundwater interactions. These geological features are essential for understanding terrain permeability, sediment load, and river morphology—all of which are central to the basin's hydromorphological analysis (Figure 2).

Figure 2. Geological map of Leshan River basin



Holocene: aQh – Alluvium: gravel, sand, silt; pQh – Proluvium: fanglomerate of rock fragments, sandy-silty deposits; dQh – Deluvium: rock fragments, sand, silt. Pleistocene: tQp – River terraces: gravel, sand; lQp – Lake sediments: gravel, sand, silt, clay. Upper Pliocene: Np² – Clastic sediments, clay, sand, gravel, partly marl, tuffite. Middle–Upper Jurassic: smJ2-3 – Tectonic mélange with olistoliths: limestone, schists, volcanic rocks. Middle–Upper Triassic: IT2-3 – Limestone, dolomite, partly cherty; fPZ2 – Phyllites, sericite schist, quartz schist, meta-sandstone. Lower Palaeozoic: sPZ1 – Epidote-chlorite and actinolitic schist, partly diabase, with marble intercalations. Source: KPMM – Geological Map of Kosovo, 1:200 000, 2006

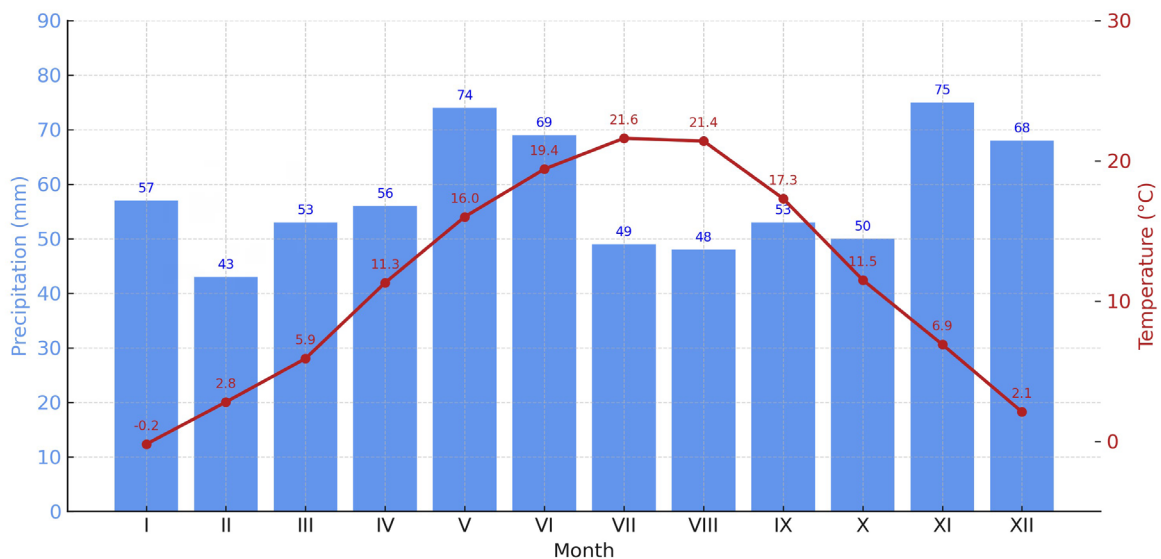
The climate of the Leshan River Basin is primarily continental, with distinct Mediterranean influences extending to Theranda and its surroundings via the White Drin Valley (Pllana, 2015). According to Ducić and Radovanović (2005), Mediterranean climatic effects are more pronounced in this area than in other parts of Kosovo. These influences are evident in the regional climate regime, characterized by dry summers and relatively mild winters. The annual average temperature in Theranda is 11.4 °C, making it one of the warmest locations in Kosovo. Solar radiation is also significant, with an annual average of 2,090 hours of sunshine. July is the sunniest month (300 hours), while December receives the least sunshine (58 hours) (Pllana, 2015).

Monthly precipitation data from nearby stations confirm the Mediterranean imprint. In Theranda, annual precipitation averages 695 mm. During the summer months—May to October—only about 293 mm falls, which coincides with the peak vegetation period and underscores the seasonal imbalance in water availability. Conversely, the cold season receives the highest rainfall, with November, December, and January being the wettest months. This seasonal distribution, characterized by dry

summers and wet winters, confirms the Mediterranean influence and highlights the need for irrigation during the growing season.

In the eastern and southeastern parts of the basin, particularly in the Sharr Mountains, sub-mountainous climatic characteristics prevail due to elevation. Temperature decreases with altitude at a lapse rate of approximately 0.29 °C per 100 m, contributing to increased precipitation in the uplands and further diversifying the basin's microclimates (Figure 3).

Figure 3. Monthly average precipitation (mm) and temperature (°C) in Therenada (1961–1990)



Source: Pllana, 2015

Data Collection and Analytical Techniques

Traditionally, watershed characteristics were studied using conventional methods; however, advancements in technology have led to the widespread use of modern tools such as Geographic Information Systems (GIS) and remote sensing, which allow for more precise and efficient analysis. In this study, these techniques were applied to examine the physical-geographical, hydrological, and geomorphological features of the Leshan River Basin.

Initially, inductive and deductive approaches were used to review and analyse existing geological, hydrological, and geomorphological studies related to the Leshan River Basin. In cases where direct data for the basin were lacking, relevant information from adjacent river basins and regional studies was incorporated to fill data gaps and ensure a more comprehensive understanding of the area's physical characteristics.

A Digital Elevation Model (DEM) of the Leshan River terrain, obtained from the Shuttle Radar Topography Mission (SRTM), was used in ArcGIS Pro 3.1.3 software to define flow direction, accumulation, and stream networks. Additionally, unmanned aerial vehicle (UAV) surveys were conducted using the AEE Toruk AP10, which is equipped with a built-in 1080p HD camera capable of capturing high-resolution aerial imagery and video. Flights were performed at altitudes ranging

from 200 to 500 meters, occasionally reaching up to 1,000 meters. The UAV captured high-resolution imagery covering parts of the Leshan River and upstream tributaries. Due to the timing of the flights in summer, vegetation canopy was fully developed in most parts of the basin. However, the UAV imagery was used primarily for visual interpretation and mapping of surface features such as river meanders and land use—not for extracting ground elevation. Ground elevation data were derived exclusively from the SRTM-based DEM. The UAV survey also supported the analysis of flood extent during the summer 2018 flood event.

Statistical and graphical methods were applied to analyse and visualize the climatic, hydrological, and topographic conditions of the Leshan River Basin. Hydrological analyses included the computation of indicators such as runoff modulus and seasonal discharge characteristics using available secondary data and field measurements. Relief characteristics—including elevation, slope, and terrain variation—were derived from the DEM processed in ArcGIS Pro 3.1.3. To assess the relationship between land surface elevation and groundwater levels, a Spearman rank correlation analysis was performed. Groundwater depth was measured manually at 285 wells across two villages during fieldwork campaigns. The corresponding land surface elevations at these measurement points were extracted from the DEM to construct the paired dataset used in the correlation analysis. This statistical method was chosen to explore monotonic relationships without assuming a normal distribution, given the natural variability in topography and groundwater conditions.

Fieldwork was an integral part of the methodology and included multiple site visits across different seasons. Measurements conducted in the field included river discharge using portable flow meters, riverbed width measurements, and groundwater level readings in domestic and agricultural wells. These primary data were collected using standardised techniques and were used to complement the remote sensing and GIS-based analyses, ensuring methodological consistency and spatial validation.

RESULTS

Physical-geographical features of the river basin

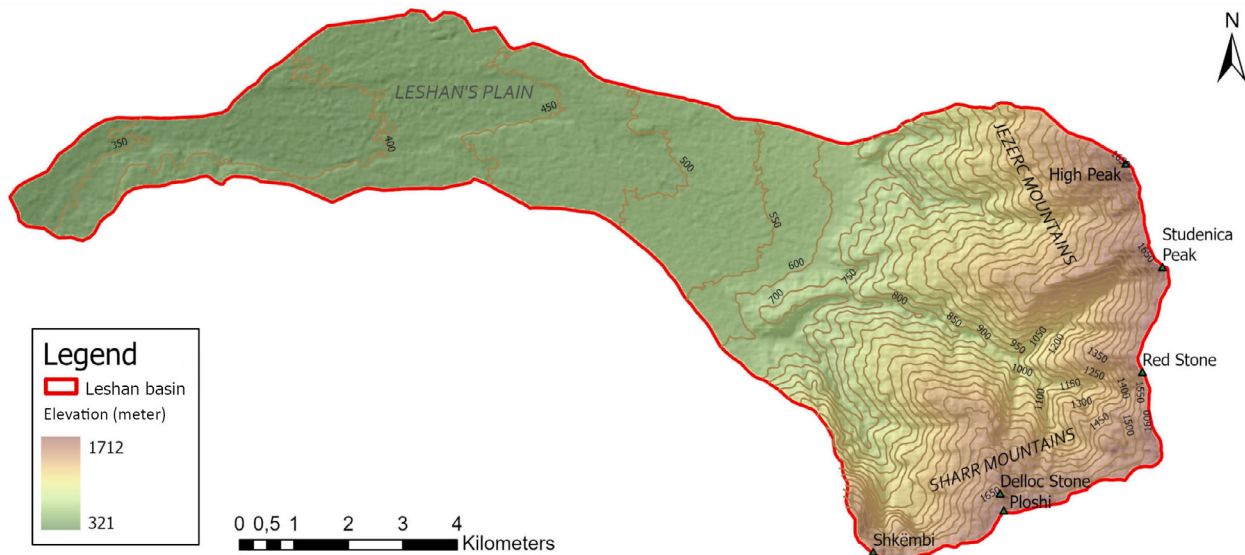
Elevation gradients within the basin vary significantly, with the lowest point located at the river mouth near Mamushë (327 m above sea level) and the highest at Studenica Peak (1,723 m) (Figure 4). Based on elevation values extracted from a Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) and processed in ArcGIS Pro 3.1.3, the basin was classified into three elevation zones: lowland (up to 600 m), foothills (600–1,000 m), and upland (above 1,000 m). These thresholds were defined through reclassification of the DEM and supported by slope layer interpretation to differentiate between gentle and steep terrain.

The lowland area, covering approximately 36 km², features relatively flat terrain primarily shaped by fluvial erosion and abrasion from the Dukagjin Pliocene Lake (Ahmetaj, 1986). The foothill zone, identified using combined elevation and slope criteria, extends across 16.5 km² and includes transitional areas toward the mountainous regions. This zone consists mainly of gravel and sand deposits that contribute to fertile soil conditions and support agricultural activity. The upland zone,

covering 28.2 km² in the eastern part of the basin, corresponds to areas exceeding 1,000 m in elevation and includes steep slopes and rugged relief. This region encompasses part of the Sharr Mountains and forms part of the watershed divide between the Toplluha and Lepenc river basins, the latter ultimately draining into the Aegean Sea.

Morphologically, the basin exhibits significant horizontal fragmentation and high relief energy, as evidenced by deeply incised valleys such as the Delloc River gorge. The watershed ridges separating the Leshan and Lepenc rivers align north–south, while the divide between the Vraniq and Mushtisht tributaries follows an east–west orientation. These morphometric characteristics illustrate how elevation and geological structure influence drainage patterns, slope distribution, and watershed delineation within the Leshan River Basin.

Figure 4. Morphological map of Leshan basin



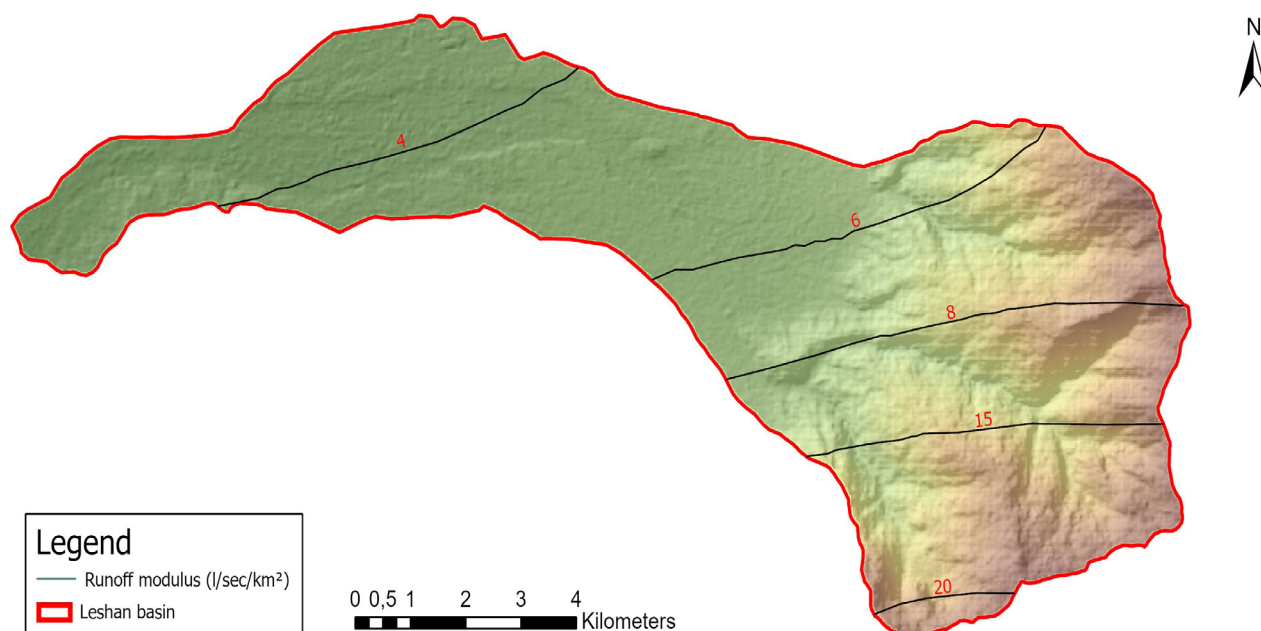
Hydrological features

The Leshan Basin covers an area of 80.7 km² and is shaped by geological, morphological, and climatic factors that influence its hydrological network. The Leshan River system comprises both permanent and temporary watercourses that drain into the main river. Watershed research is crucial for preventing soil erosion, conserving water, and promoting sustainable development (Waikar & Nilawar, 2014). The river originates at the confluence of its two principal tributaries—the Vraniq and Mushtisht rivers (the latter historically known as the Black River)—and flows for 15.99 km. Flow rates along the river are influenced by seasonal precipitation, elevation gradients, and subsurface contributions from groundwater.

Specific runoff was calculated using hydrological data collected at the river's outflow point near Mamushë, based on discharge measurements taken during fieldwork in 2018–2019 and supplemented with hydrological data from other researchers working in the area. The average specific runoff for the Leshan Basin was estimated at 8.64 l/s/km², compared to 7.39 l/s/km² for the broader Toplluha Basin (Avdullahi et al., 2008). These values reflect spatial variations in precipitation across the basin. In the

southeastern upland areas, where elevation is higher and orographic effects intensify rainfall, specific runoff exceeds 20 l/s/km², with mean annual precipitation surpassing 1,100 mm (Pllana, 2015). In contrast, the lower western part of the basin receives less than 700 mm annually, resulting in specific runoff values below 4 l/s/km² (Figure 5).

Figure 5. Specific runoff map for Leshan basin



The Leshan River's regime is classified as nival-pluvial (Živković & Gavrilović, 2009). Its tributaries extend to elevations above 1,700 m, where significant snowfall occurs from late fall through early spring. Snowmelt contributes to substantial water runoff and spring freshets. Hydrological input from the Sharr Mountain—particularly from the Toplluha River's left tributaries—is highest during late spring.

The river exhibits marked flow variability in response to precipitation events and seasonal changes. This variability was observed through flow measurements taken during field campaigns. For example, on October 13, 2018, following heavy rainfall, the flow rate was recorded at 141 l/s, while during an extended dry period on August 13, 2019, it dropped to 30.6 l/s. These dates were selected as representative of high-flow and low-flow conditions during the monitoring period, illustrating the range of seasonal variation. River level measurements during low-flow periods ranged from just a few centimeters to 29 cm in wider sections, and up to 130 cm in narrower channel segments.

The Leshan River flows through a wide floodplain composed of alluvial deposits with high porosity, which facilitates substantial water infiltration and enhances groundwater recharge. The connection between surface water and groundwater is especially pronounced in summer, when reduced surface runoff increases the relative contribution of groundwater to streamflow. For instance, during the dry season, surface flow in the village of Sopi is nearly absent, whereas a few kilometers downstream, in the village of Leshan, the river maintains a flow sufficient for irrigation. This suggests that groundwater discharge into the river is spatially variable and strongly influenced by the

alluvial structure and hydrogeological connectivity of the basin. While summer conditions reveal this relationship more clearly, winter dynamics are less discernible due to elevated surface runoff masking groundwater contributions. Additionally, the presence of permeable geological layers—including fractured limestone and alluvial gravels—contributes to subsurface flow exchange.

To assess the relationship between land surface elevation and groundwater levels in the Leshan River basin, Spearman's rank correlation analysis was conducted using field measurements from two villages: Leshan (188 data points) and Tërrnje (97 data points). Groundwater levels were recorded from wells commonly used by local residents for drinking water. Elevation data were collected using a Garmin eTrex 32x GPS device to determine the altitude of each well location. Groundwater depths were measured manually using handheld measuring meters, and groundwater level at each point was calculated by subtracting the measured depth from the corresponding surface altitude recorded by the GPS device. For each location, ranks were assigned to both elevation and groundwater level values, and the Spearman rank correlation coefficient (ρ) was calculated to determine the strength and direction of the monotonic relationship. The coefficient was computed using the formula (Spearman, 1904):

$$\rho = 1 - (6 * \sum d^2) / (n(n^2 - 1))$$

where d is the difference between the ranks of each pair of observations, and n is the total number of paired values. This non-parametric method is suitable for evaluating correlations between variables when the assumptions of normality are not met. The results indicated a very strong positive association between land surface elevation and groundwater levels in both areas. In the village of Leshan, the correlation coefficient was $\rho = 0.98$, while in Tërrnje it was $\rho = 0.84$. These findings suggest that groundwater levels are closely linked to surface topography, with higher elevations generally corresponding to higher groundwater levels. The strong correlation supports the use of elevation data as a reliable predictor for understanding groundwater distribution patterns across the basin (Figure 6–7).

Figure 6. Correlation between land altitude and groundwater in village of Leshan

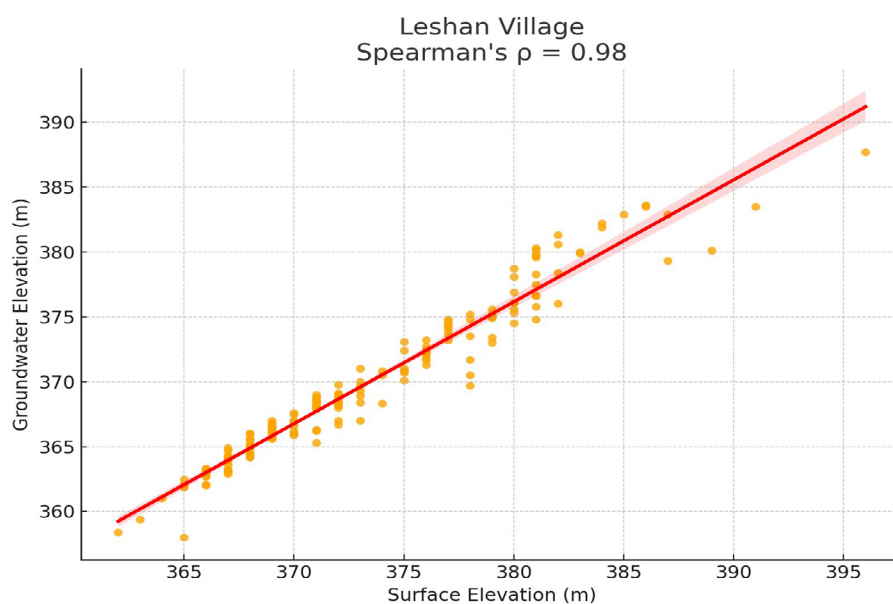
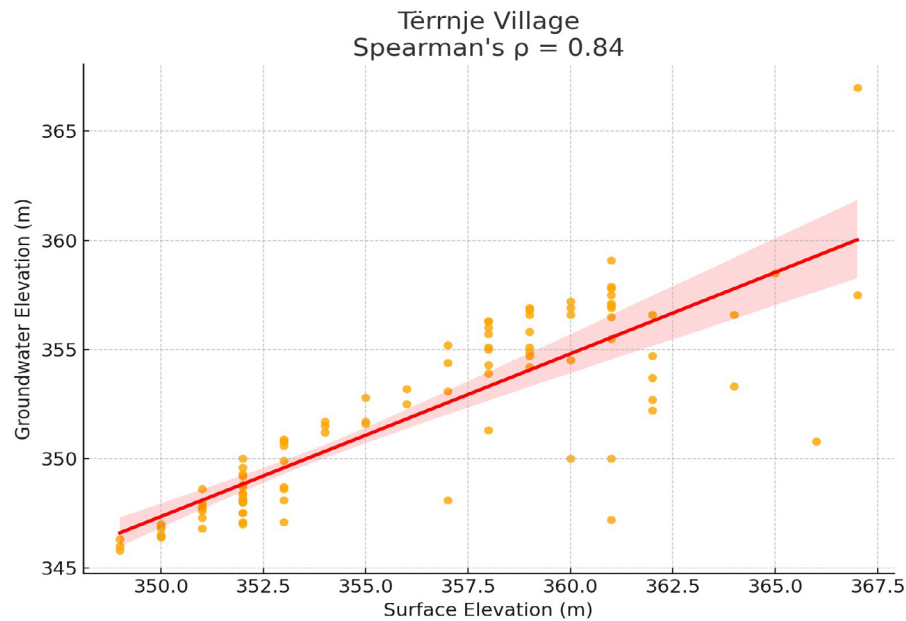


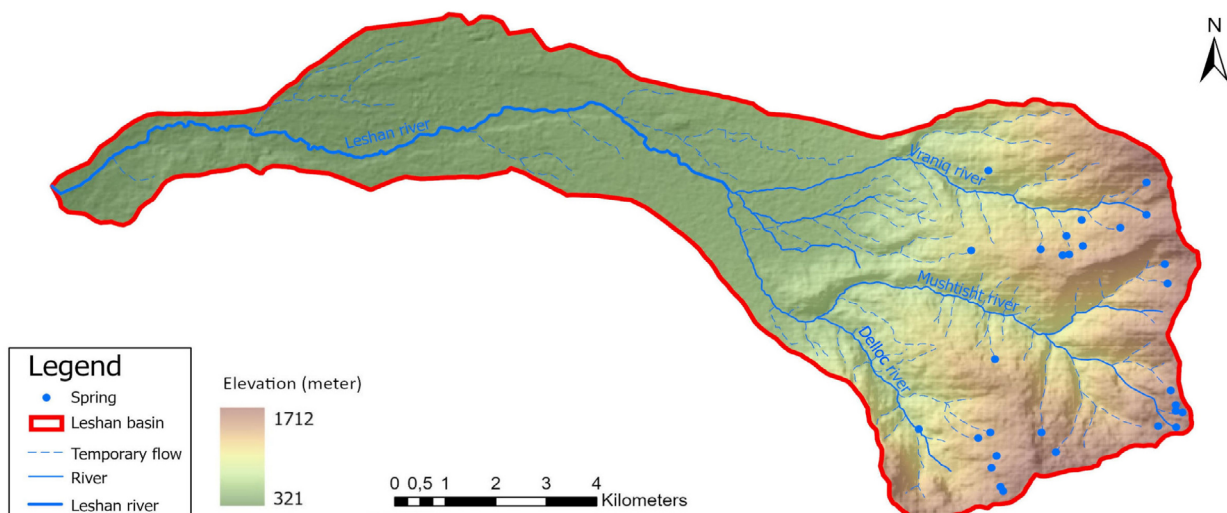
Figure 7. Correlation between land altitude and groundwater in village of Tërrnje



Despite the widespread river network in the Leshan Basin—particularly in its hilly and mountainous areas—water resources remain modest. The main tributaries of the Leshan River, the Vraniq and Mushtisht rivers, have steep gradients, with the Vraniq River descending 990 m (115 m/km) and the Mushtisht River 1,153 m (104.8 m/km), indicating significant turbulence. The Mushtisht River's main tributary, the Delloc River, flows through a deep valley with canyon-like features over its 4.2 km course.

The basin's drainage pattern is characterized by tributaries joining the main river at narrow, oblique angles, forming a diagonal hydrographic system. This pattern likely reflects structural controls—such as fault alignments or the orientation of bedrock strata—that influence the direction of channel development. Combined with broad valleys, deep gorges, and the Leshan River's predominantly normal valley morphology, this hydrographic configuration highlights the basin's geological complexity and geomorphic diversity (Figure 8).

Figure 8. Leshan River system



Geomorphic features

The geomorphic features of the Leshan River Basin reflect considerable variation in elevation, with the upstream and eastern parts dominated by high mountain ridges, and the downstream segment transitioning into a lowland river system. While the upper reaches are clearly defined by steep relief and natural watershed divides, the middle and lower sections of the basin are flatter, which may reduce the visibility of surface drainage boundaries. Nevertheless, delineation of the watershed was feasible using elevation data, and the high-relief zones in the eastern part of the basin—particularly around the main tributaries—provide clear topographic markers for the watershed boundary.

Table 1. Morphometric parameters calculated for the Leshan river²

Parameters	Formulae/methods	Units	References
Areal/shape aspects			
Area of the watershed (A)	GIS analysis	Km ²	
Perimeter of the watershed (P)	GIS analysis	Kilometre	
Basin length (L_b)	$L_b = (1.312 \times A^{0.568})$	Kilometre	Nookaratnam et al. (2005)
Basin width		Kilometre	
Elongation ratio (R_e)	$R_e = (2\sqrt{(A/\pi)}) / L_b$	Dimensionless	Schumm (1956)
Linear aspects			
Stream order (U)	Hierarchical rank	Dimensionless	Horton (1945)
Stream length (L_u)	$L_u = L_{u1} + L_{u2} + L_{u3} + \dots + L_{un}$	Kilometre	Horton (1945)
Mean stream length (L_{sm})	$L_{sm} = (L_u / N_u)$	Kilometre	Horton (1945)
Stream number (N_u)	$N_u = N_{u1} + N_{u2} + N_{u3} + \dots + N_{un}$	Dimensionless	Horton (1945)
Bifurcation ratio (R_b)	$R_b = N_u / N_{u+1}$	Dimensionless	Schumm (1956)
Mean bifurcation ratio (R_{bm})	Average of bifurcation ratio of all orders	Dimensionless	Strahler (1957)
Mean stream length ratio (R_{lm})	Average of the steam length ratio of all orders	Dimensionless	Schumm (1956)
Stream length ratio (R_l)	$R_l = L_u / L_{u-1}$	Dimensionless	Horton (1945)
Stream frequency (F_s)	$F_s = (\sum N_u) / A$	km ⁻²	Schumm (1956)
Drainage density (D_d)	$D_d = (\sum L_u) / A$	km/km ²	Schumm (1956)
Drainage texture (D_t)	$D_t = (\sum N_u) / P$	km ⁻¹	Schumm (1956)
Drainage intensity (D_i)	$D_i = F_s / D_d$	km ⁻¹	Faniran (1968)
Constant of channel maintenance (C_{cm})	$C_{cm} = 1 / D_d$	km ² /km	Schumm (1956)
Relief aspects			
Maximum elevation (H)	GIS analysis	Metre	
Minimum elevation (h)	GIS analysis	Metre	
Relief (B_h)	$B_h = H-h$	Kilometre	Strahler (1952)
Basin asymmetry	Asymmetry of the basin's slopes (left and right banks)	Dimensionless	
Drainage system	Drainage patterns	Dimensionless	Horton (1945)
Valley type	GIS analysis	Dimensionless	Schumm (1977)
River terraces	GIS analysis	Dimensionless	
River width	GIS analysis	Metre	
River flow	GIS analysis	Dimensionless	
River meanders	GIS analysis	Dimensionless	Wolman and Leopold (1957)
River profile	GIS analysis	Dimensionless	Hack (1957)

² Adapted from Shekar and Mathew (2022)

Areal/shape aspects

The size and shape of a river basin influence its hydrological behavior, particularly its potential water volume and flow dynamics. The Leshan River catchment has an elongated form, with its main flow direction oriented from east to west, shaped by the regional slope of the Dukagjin Plain. It originates on the western slopes of the Sharr Mountain in the east and extends toward its confluence with the Toplluha River in the western part of the basin. The basin perimeter, representing the total length of its outer boundary (Khan, 2021), measures 55.2 kilometers. The relative perimeter, calculated as the ratio of basin area to perimeter, is 1.46 for the Leshan River.

Another important characteristic is the basin's length and width. The Leshan River basin stretches 22.5 km in length and has an average width of 3.58 km, emphasizing its elongated form. This elongation is attributed to active tectonic processes and the geological evolution of the terrain (Gaidzik & Ramírez-Herrera, 2017).

The elongation ratio is a dimensionless index that reflects the shape of the basin and its hydrological behavior (Schumm, 1956). It is calculated using the formula:

$$R_e = \frac{2\sqrt{A/\pi}}{L_b}$$

A lower elongation ratio—such as that of the Leshan River Basin ($R_e = 0.45$)—indicates an elongated catchment. This shape tends to delay peak flows, resulting in a more gradual hydrological response. Such basin configurations are generally less prone to flash flooding, especially when considered alongside moderate drainage density and stream frequency values.

Linear Aspects

According to Horton's classification (1945), the branching complexity of the Leshan River system reaches up to the 5th order (Table 1).

Table 2. Longitudinal aspect of the Leshan basin

Stream order	Stream number (N_u)	Stream length (L_u) in km	Mean stream length (L_{sm}) in km	Bifurcation ratio (R_b)	Stream length ratio (R_l)
1	68	56.54	0.83	-	-
2	18	29.3	1.62	3.78	0.52
3	3	10.01	3.33	6	0.34
4	2	14.35	7.18	1.5	1.43
5	1	24.61	24.61	1	1.71
TOTAL	92	134.8		12.28	
MEAN			1.47	3.07	1.0

The number of first-order streams is 68, with an average length of 830 m, indicating steep terrain. In contrast, the fifth-order stream—corresponding to the Leshan River itself and the Vraniq River—is 24.61 km long. In general, the total length of streams is greatest in first-order branches and decreases with increasing stream order. This pattern reflects intense erosion within the basin and variability in lithology and topography in certain areas (Singh & Singh, 1997; Vittala et al., 2004; Chopra et al., 2005). The mean stream length, defined as the ratio of the total stream length to the number of streams (Horton, 1945), is calculated in this study to be 1.47 km.

The bifurcation ratio (R_b) measures the relationship between the number of streams in successive orders. It is calculated by dividing the number of streams in a given order (N_n) by the number of streams in the next higher order (N_{n+1}) (Schumm, 1956). In the Leshan River basin, third-order streams exhibit the highest bifurcation ratio, reaching a value of 6. To provide a broader understanding of the branching pattern, Strahler (1957) introduced the mean bifurcation ratio (R_{bm}), calculated as the weighted average of bifurcation ratios across all stream orders. In this study, the mean bifurcation ratio was found to be 3.07.

The stream length ratio (R_l) represents the ratio between the average lengths of streams of successive orders (Horton, 1945). In the Leshan River basin, the highest stream length ratio is recorded for the Leshan River itself, with a value of 1.71. The mean stream length ratio (R_{lm}), calculated as the average of all stream length ratios across the basin, is 1.00.

Stream frequency (F_s) measures the number of streams per unit area and is calculated by dividing the total number of streams by the catchment area (Horton, 1932; Schumm, 1956). It reflects how densely streams are distributed across the landscape. In the Leshan River basin, stream frequency is 1.14 km^{-2} . This value shows a positive relationship with drainage density, indicating that areas with more streams tend to exhibit higher drainage densities.

The hydrological analysis of the Leshan River basin involved calculating drainage density, influenced by factors such as annual runoff (Morisawa, 1962), rainfall intensity (Chorley & Morgan, 1962), rock resistance (Zăvoianu, 1985), permeability (Strahler, 1956), vegetation cover (Chorley, 1957), and the texture of landscape dissection and stream spacing (Chorley, 1969). Drainage density (D_d) is defined as the ratio of the total length of all stream segments to the basin area projected onto a horizontal plane. For the Leshan River basin, drainage density was calculated at 1.67 km/km^2 , with the highest values observed in the eastern sector, particularly around the Jezerc and Sharr Mountains. Drainage texture (D_t), as defined by Schumm (1956), is the ratio of the total number of streams to the basin perimeter. In this study, drainage texture was found to be 1.67 km^{-1} . Drainage intensity (D_i), representing the ratio of stream frequency to drainage density (Faniran, 1968), was calculated as 0.68 km^{-1} .

The constant of channel maintenance (C_{cm}) is the inverse of drainage density and represents the area of the catchment (in square kilometers) required to support one kilometer of stream segment (Schumm, 1956). For the Leshan River basin, the constant of channel maintenance is calculated to be $0.60 \text{ km}^2/\text{km}$.

Relief Aspects

Basin relief—defined as the difference in elevation between the highest and lowest points within the catchment's perimeter (Strahler, 1952)—is a key indicator of topographic variability. In the Leshan River basin, the maximum elevation is observed at Studenica Peak (1,723 m a.s.l.), while the minimum elevation occurs at the river mouth near Mamushë (327 m a.s.l.). Thus, the total basin relief is calculated to be 1,396 metres.

The Leshan River basin displays a pronounced asymmetry, with a left-to-right bank area ratio of 1:1.98. This asymmetry is attributed to the steeper slopes on the southern side of the river, in contrast to the gentler, more gradual slopes descending toward the river from the northern side.

The drainage system refers to the spatial arrangement of streams, rivers, and associated water bodies within a basin (Ritter, 2006). The Leshan River basin exhibits a dendritic drainage pattern, characterized by tributaries converging at narrow angles. This configuration is shaped by the regional relief, tectonic activity, and underlying geological structures (Figure 8).

Extending primarily in an east–west direction, the Leshan River forms a broad lowland valley up to 500 metres wide. The main channel exhibits a typical morphological valley profile. In contrast, its tributaries—particularly those originating in mountainous terrain—form narrower, deeper valleys with gorge-like or canyon-like characteristics. Notable examples include the Vraniq, Mushtisht, and Delloc rivers, the latter of which flows through a canyon in certain segments.

The Leshan River features predominantly accumulative terraces, formed through the deposition of alluvial sediments. These terraces are mostly located along the middle and lower stretches of the river. Additionally, the river contains temporary sediment islands, which are frequently submerged during high-flow conditions and may shift or disappear following such events.

The river's width varies substantially along its course, ranging from less than 2 metres in upstream segments to over 8 metres in wider reaches. Corresponding depths range from a few centimetres up to 130 centimetres under normal conditions. These parameters can change dramatically during flood events. The most recent flood, which occurred on August 15–16, 2018, following intense rainfall, caused the river to overflow and reach a maximum width of over 110 metres.

The Leshan River exhibits dynamic flow characteristics, particularly in its lowland portions, where flow variability is more pronounced. Historical evidence, including sediment deposits and vegetation patterns, indicates that the river has shifted its course over time. Earlier flow paths appear to have extended further north than the current channel.

As a lowland river, the Leshan River displays well-developed meanders along its course. Free meanders are evident in the main channel (Figure 9), while its tributaries also exhibit sinuous paths within their respective valleys, mimicking the main river's pattern. A comparison with historical maps reveals an increase in meander amplitude over time, indicative of ongoing processes of bank erosion and sediment deposition.

The longitudinal profile of the Leshan River illustrates the change in elevation from its source to its confluence with the Toplluha River (Figure 10). Reflecting its lowland character, the Leshan River experiences a relatively modest elevation drop along its course, particularly when compared to its steeper tributaries, such as the Vraniq and Mushtisht rivers. In the upper section, the river exhibits a slightly steeper gradient, facilitating faster flow. However, the middle and lower sections are marked by a more gradual decline in elevation, which contributes to the development of pronounced meanders and a slower, more sinuous flow pattern in these downstream areas.

Figure 9. Orthophoto - Meander of the river Leshan

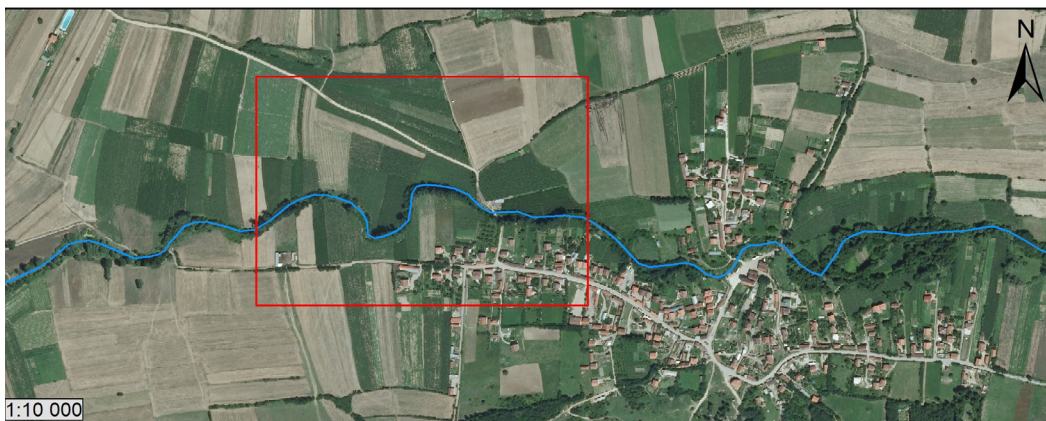
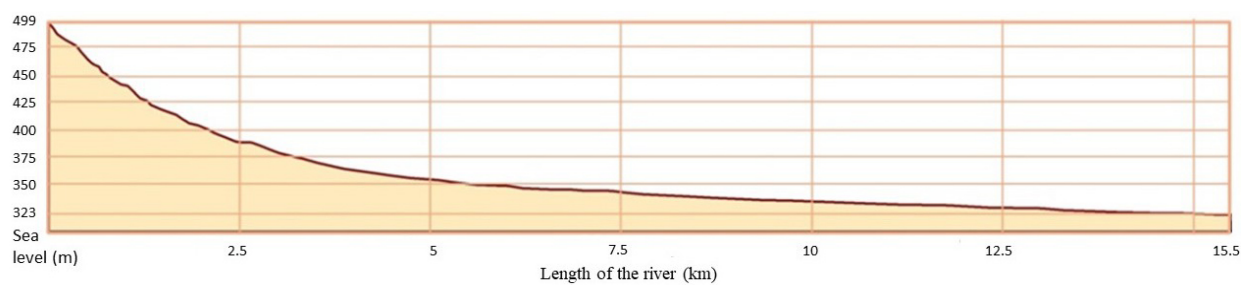


Figure 10. Longitudinal profile of the Leshan River



CONCLUSIONS

Seasonal variability exerts a substantial influence on the discharge regime of the Leshan River. Summer months are characterised by reduced flows, whereas higher discharges occur during winter and late spring, primarily driven by snowmelt and rainfall. These fluctuations reflect the dual climatic influences of continental and Mediterranean systems—continental patterns contribute to snow accumulation in colder months, while Mediterranean conditions increase pluvial inputs during warmer periods.

The geomorphological evolution of the basin illustrates the dynamic nature of its fluvial systems. Evidence of historical channel migration, sedimentation patterns, and vegetation traces along abandoned riverbeds provide insights into the basin's palaeohydrological development. These findings highlight the value of geomorphological analyses in reconstructing long-term fluvial processes and landscape transformations.

Groundwater contributes critically to sustaining river flow, particularly in dry seasons. Upstream of the village of Sopi, the river nearly dries out during summer, while downstream near Leshan, adequate flow persists for irrigation purposes. This continuity is sustained by groundwater recharge zones located between Leshan, Shirokë, Sopi, and Gjinoc. The strong correlation between groundwater levels and surface elevation ($\rho = 0.98$ in Leshan; $\rho = 0.84$ in Tërrnje) underscores the close interplay between surface and subsurface hydrological systems, emphasizing the need to integrate groundwater dynamics into water resource management strategies.

Topographic asymmetry, with steeper southern slopes compared to the gentler northern bank, reflects differential erosion processes that shape valley morphology and contribute to the basin's landscape heterogeneity. The tributaries' narrow-angle junctions and the diagonal hydrographic pattern are likely influenced by structural controls, such as fault alignments and lithological variations. These tectonic influences have guided fluvial development and continue to shape present-day drainage configurations.

This study applied a comprehensive morphometric analysis to assess the Leshan River basin, focusing on the relationship between basin geometry, topography, and hydrological response. The catchment's elongated form, steep relief, and diverse geology significantly affect flow dynamics and drainage efficiency. The elongation ratio ($R_e = 0.45$) and form factor corroborate the basin's predisposition to concentrated surface runoff, particularly in the upstream sections with steeper gradients and pronounced dissection.

The calculated drainage density (1.67 km/km^2) and stream frequency (1.14 km^{-2}) indicate moderate runoff potential and infiltration capacity. However, the high bifurcation ratio observed in third-order streams suggests a localised susceptibility to rapid surface runoff. Asymmetrical terrain and differential slope gradients further influence sediment transport and erosion patterns, intensifying geomorphic activity along the southern bank.

The basin's diagonal drainage geometry, shaped by oblique tributary confluences, further supports the hypothesis of tectonic and lithological controls influencing drainage evolution. This geomorphometric configuration adds to the basin's structural complexity and informs its hydrological behaviour.

The observed strong correlation between elevation and groundwater levels confirms significant vertical hydrological connectivity. This relationship, along with the presence of permeable alluvial deposits, reinforces the role of groundwater in maintaining river flow during low-discharge periods.

These insights offer several implications for applied watershed management. First, the upstream areas of the basin, where steep gradients and limited infiltration capacity dominate, should be prioritized for erosion control measures and interventions aimed at mitigating flash floods. In addition, due to the spatial variability in groundwater–surface water interactions, it is essential to integrate subsurface hydrology into long-term water resource planning, particularly in regions where agriculture relies heavily on irrigation. Lastly, the morphometric configuration of the basin—with its obliquely converging tributaries and sediment-laden flows—calls for targeted monitoring of the tributary systems, as these features may increase flood risk and sedimentation downstream.

Future research should incorporate high-resolution digital elevation models (DEMs), continuous stream gauge data, and detailed land use information to improve hydrological modelling and flood risk assessments. These efforts are essential for the sustainable management of the Leshan River basin, hazard mitigation, and informed infrastructure development in this topographically and geologically complex landscape.

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Geospatial Assessment of Vegetation Dynamics and Climate Impact on Sustainable Urbanism: A Case Study of Adi Town, Benue, Nigeria

ABSTRACT

Vegetation is one of the most important renewable resources of the Earth's ecosystem. However, vegetation has been in a high state of decline both globally and locally. With the increase in urbanization across the globe, city microclimates are constantly changing, affecting the living environment and necessitating the need for sustainable urbanism. This research investigated the rate of vegetation degradation, assessed the influence of climate and human activities on vegetation loss, and aimed to inform mitigation strategies and promote sustainable urban development. The research applied a Normalized Difference Vegetation Index (NDVI) derived from Landsat imagery using supervised classification, and maximum likelihood classification was employed for the reclassification of different land uses. A bivariate linear regression of NDVI values and rainfall data was conducted to evaluate the relationship between vegetation cover and climatic variables. The NDVI results showed a significant decrease in vegetation over the study period, while built-up areas and agricultural land expanded. The relationship between climate and vegetation was found to be weak, while human activities contributed massively to the degradation of vegetation. Agricultural practices, brick burning, deforestation, urbanization, and fuelwood collection emerged as the major drivers of vegetation loss. The study recommends public awareness campaigns on the importance of vegetation, large-scale afforestation policies, investment in agricultural innovation to reduce land pressure, the expansion of automated meteorological stations, and urgent climate change mitigation measures to promote environmental sustainability and resilient urban development.

Keywords: vegetation, sustainable urbanism, climate change, vegetation analysis, Geographic Information System (GIS), Remote Sensing (RS)

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INTRODUCTION

The surge in the growth of cities calls for an in-depth study of the spatial, physical, and socio-economic characteristics of cities. Urbanism can be traced back to the assumptions of certain theories of urban development. Research into ancient urbanism is shaped by the legacy of concepts, ideas, perspectives, and conjectures put forth by past scholars like Weber, Childe, Wheatley, and Mumford, as well as by the contributions of geographers such as Von Thünen, Christaller, Lösch, Berry, and C. Smith Adams (Cowgill, 2004). The concept of urbanism was formed in the 19th century by the Spanish engineer Ildefons Cerda and later popularized by Wirth, who defined “urbanism as a way of life” of the city inhabitants (Cowgill, 2004; Wirth, 1938; Lewicka et al., 2015). It later broadened to encapsulate the examination of the interactions between urban inhabitants and the built environment (Raptis, 2017). Urbanism encompasses the comprehensive examination of cities, including their geographical, economic, political, social, and cultural aspects, along with the influence of these factors on the constructed environment. If urbanization is the progression through which an urban area evolves, urbanism represents its resultant state. It encompasses all the physical and social interactions observed within urban centers, reflecting the amalgamation of social, economic, and political forces and processes inherent in these settings. Urbanism provides a nuanced comprehension of the distinctive ways of life inherent to urban environments, offering insight into their characteristic features and dynamics (Gopan, 2021).

Vegetation is one of the most important components of the Earth’s land ecosystem. Vegetation provides a wide range of social and environmental services and benefits for the sustainability of ecosystems. For example, urban vegetation can sequester carbon, regulate microclimates, improve air quality through photosynthesis, preserve biodiversity, and conserve soil and water (Jin et al., 2018a), thus creating a need to integrate vegetation into the urban environment. Unfortunately, recent studies show that vegetation has been influenced by human disturbances and climate change in long-term landscape evolution (Adewumi, 2013; Jin et al., 2018a).

Vegetation analysis can generally be divided into two categories: classification and ordination. Classification groups vegetation sample stands into relatively homogeneous units, while ordination explores the relationships between individual sample stands (Causton, 1988). One method for conducting vegetation analysis is through the use of the Normalized Difference Vegetation Index (NDVI). NDVI has become widely popular and frequently used in vegetation studies due to its effective indices or band combinations. It is less influenced by soil properties and is particularly useful for analyzing vegetation characteristics that can be indirectly interpreted from object colors, as seen in raster images (Lemenkova, 2012).

The United Nations defines sustainability as a concept that emphasizes meeting the needs of the present generation without compromising the ability of future generations to fulfill their own needs (Klarin, 2018). Sustainable urbanism has been described as urban development that promotes walkability and accessibility to public transportation, complemented by high-performance buildings and



infrastructure. This approach prioritizes compactness (density) and biophilia (human connection to nature) as central tenets of sustainable urban design (Stevens et al., 2010). Sustainable urbanism can, therefore, be referred to as the interaction of urban inhabitants with the city environment and the maintenance of urban use for future generations.

Nigeria, like many other developing countries, is facing urban challenges due to the effects of climate change (Department of Climate Change, 2021). These effects are mainly induced by human activities. In 2015, the United Nations, of which Nigeria is a member, highlighted the need for sustainable cities and climate change action. The UN expects signatory members to incorporate climate change measures into the frameworks of national policies, strategies, and planning processes.

Due to the constant changes in the vegetation of the study area, it has become imperative to understand the current status of the vegetation, the rate of change, and the effects of climate on these changes. This study focuses on the rate of vegetation change and its impacts on the environment in Adi town. The research objectives seek to determine the status and rate of vegetation change in Adi, as well as to assess the effects of climate on vegetation change in the area.

LITERATURE REVIEW

Sustainable Urbanism and Vegetation Degradation

There is a global increase in the growth of cities in terms of both population and intensity of land use. These factors affect the way in which cities' activities are carried out. It was these changes in urban lifestyles that drew the attention of the Spanish engineer Ildefons Cerda to coin the concept of urbanism (Wirth, 1938). Since then, the concept has acquired various meanings and applications. Among the early scholars, Wirth was particularly influential, defining "urbanism as a way of life" of the city inhabitants (Wirth, 1938; Lewicka et al., 2015). There is no doubt that "Cities change societies and societies change cities" (Raptis, 2017). Cities foster social dynamics, where diverse and sometimes opposing ideas coexist, in turn shaping the environments around them (Raptis, 2017).

Scientific research confirms the link between urban lifestyles and impacts such as climate change—an uncontrollable force leading to numerous devastating issues. However, the extent and severity of these problems are not consistently reflected in the evolution of urbanism as a concept. Urbanism progressed slowly and systematically until the industrial age, which was marked by the emergence of the master plan concept devised by technocrats, known as rational urbanism. This approach persisted during the modernist movement but faced criticism with the rise of failed urban designs. In response, new theories such as new urbanism, landscape urbanism, cooperative urbanism, and tactical urbanism gained traction. However, the evolution of urbanism theories did not keep pace with rapid urbanization, leading to both exceptional urban developments and the proliferation of contemporary urban challenges (Carrizosa, 2022; Raptis, 2017).

The development of sustainable urbanization is multi-dimensional and multi-disciplinary (United Nations Department of Economic and Social Affairs, 2007; World Economic and Social Survey, 2013). Developing sustainable cities necessitates integration and coordination across various sectors. For instance, an effective land plan should encompass areas designated for industry, residential housing, and green spaces, seamlessly integrated with provisions for accessible public transportation. Synergies in investing in green infrastructure could lead to a decrease in greenhouse gas emissions, while the preservation of green spaces might involve the management of groundwater sources. Likewise, within sectors such as transportation, integration entails establishing connections among different modes of transportation (such as buses, trams, metros, bicycles, and walking) to minimize travel time, emissions, and reliance on private vehicles (World Economic and Social Survey, 2013).

National Sustainable Development Strategies (NSDSs) have no standardized blueprints and vary significantly across countries in terms of structure and content, being intricately linked with each country's national institutional framework for policy planning and implementation (United Nations Department of Economic and Social Affairs, 2007). Therefore, differences exist in how climate change is addressed within NSDSs, both in terms of the level of importance assigned to it and the variations in relevant national institutional structures. Countries are required to identify various areas of city management, such as sustainable resource management, sustainable consumption and production, global responsibility, and sustainable economic development, and to define clear objectives as well as list explicit aims and actions (United Nations Department of Economic and Social Affairs, 2007).

Muoghalu (2009) identified the basic causes of vegetation degradation, namely natural and human factors. The natural factors are climatic and edaphic, while the human activities are primarily due to urbanization, deforestation, and bush burning. Soil, aspect, and gradient are determining factors in vegetation growth, while precipitation plays the most important role in vegetation development (Chaulagain & Shrestha–Malla, 2018; Moody & Hickey, 2025; Muoghalu, 2009; Nam, 2015).

Vegetation in a geographical region is largely shaped by the area's climatic conditions (Herrmann et al., 2005). In Nigeria, the country's vegetation belts closely correspond to its climatic zones. Among all climatic factors, rainfall plays the most significant role in determining vegetation distribution, particularly in tropical regions. In Nigeria, there is a gradual decrease in both rainfall and the duration of the wet season from the south to the north. This decline has a strong influence on the formation of distinct vegetation zones, with transitional areas marking the shifts between belts. It is estimated that the desert is encroaching at a rate of 0.6 km per year in Northern Nigeria (Ebenezer, 2015).

Methods of Analyzing Vegetation Degradation

Before remote sensing revolutionized data collection methods, the primary way of gathering vegetation data was through traditional techniques. This involved direct field measurements and observations. While this approach tends to be more accurate, it is also time-consuming and financially demanding (Getheko & Medany, 2006, 2007; Iheariorochi & Iloabuchi, 2012). Today, satellite remote sensing has



become a crucial tool for monitoring, detecting, quantifying, and mapping land cover patterns and changes. Its advantages include wide spatial coverage, the ability to acquire data repeatedly, a digital format suitable for computer analysis, and precise geo-referencing techniques (Adejato et al., 2018).

In recent years, numerous remotely sensed images have been obtained using a variety of airborne and spaceborne sensors. These images, captured by multispectral and hyperspectral sensors, cover different parts of the electromagnetic spectrum, with wavelengths ranging from the visible to the microwave regions (Iheaniorochi & Iloabuchi, 2012).

The National Center for Geographic Information and Analysis (NCGIA, 1990) defines a Geographic Information System (GIS) as “a system of hardware, software, and procedures designed to facilitate the management, manipulation, analysis, modeling, representation, and display of geo-referenced data to address complex problems related to resource planning and management.” The introduction of GIS has also enabled the integration of multi-source and multi-temporal data, allowing for the analysis of changes in land surface components, including trends, rates, nature, locations, and magnitudes of those changes (Adejato et al., 2018).

A Normalized Difference Vegetation Index (NDVI) is a basic mathematical formula used to assess the probability that vegetation is actively growing at a specific location during the time of observation (Ceccato & Dinku, 2010). NDVI measures vegetation greenness using spectral data, correlating with photosynthesis and productivity, making it a key tool for vegetation analysis (Ceccato & Dinku, 2010). It quantifies vegetation greenness by calculating the difference in spectral reflectance between the red and near-infrared wavelength regions using the formula: $[(NIR - red) / (NIR + red)]$.

Despite some limitations, NDVI remains the most commonly applied method for assessing vegetation changes due to its effectiveness in capturing variations in green vegetation (Herrmann et al., 2005; B. Li et al., 2011).

METHODS

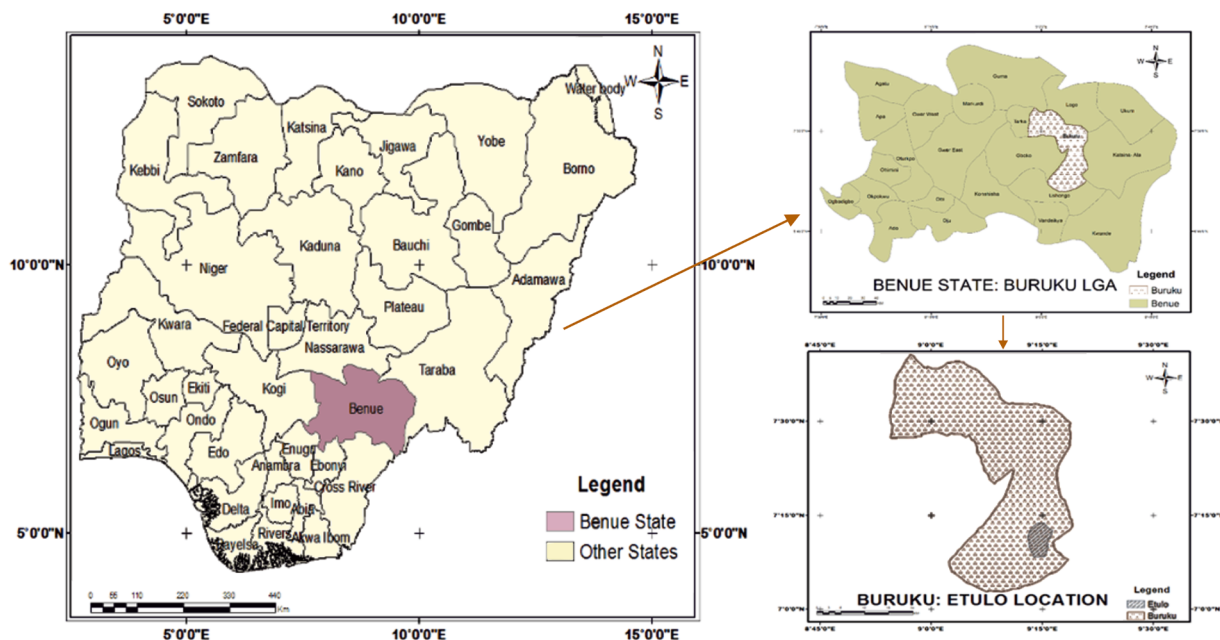
Study Area and Data Sources

Adi is located between latitudes 07°09'00"N and 07°12'36"N and longitudes 09°14'24"E and 09°16'12"E (USGS, 2019, Figure 1–2). It is situated in Buruku Local Government Area of Benue State, Nigeria. Based on Köppen's climate classification, Adi belongs to the tropical wet and dry (Aw) climate, which is characterized by a tropical rainy season and a tropical dry season. The rainy season lasts for about seven months, with annual rainfall ranging between 1,200–2,000 mm, usually from April to October. The dry season extends from November to March (Adamgbe & Ujoh, 2012; Akpen et al., 2019).

Adi experiences high temperatures, with average values ranging from 28°C to 32°C, sometimes reaching as high as 37°C (Adamgbe & Ujoh, 2012; Akpen et al., 2019; Hula, 2010). The vegetation type in the study area is guinea savannah, consisting of short grasses and scattered trees, but it has under-

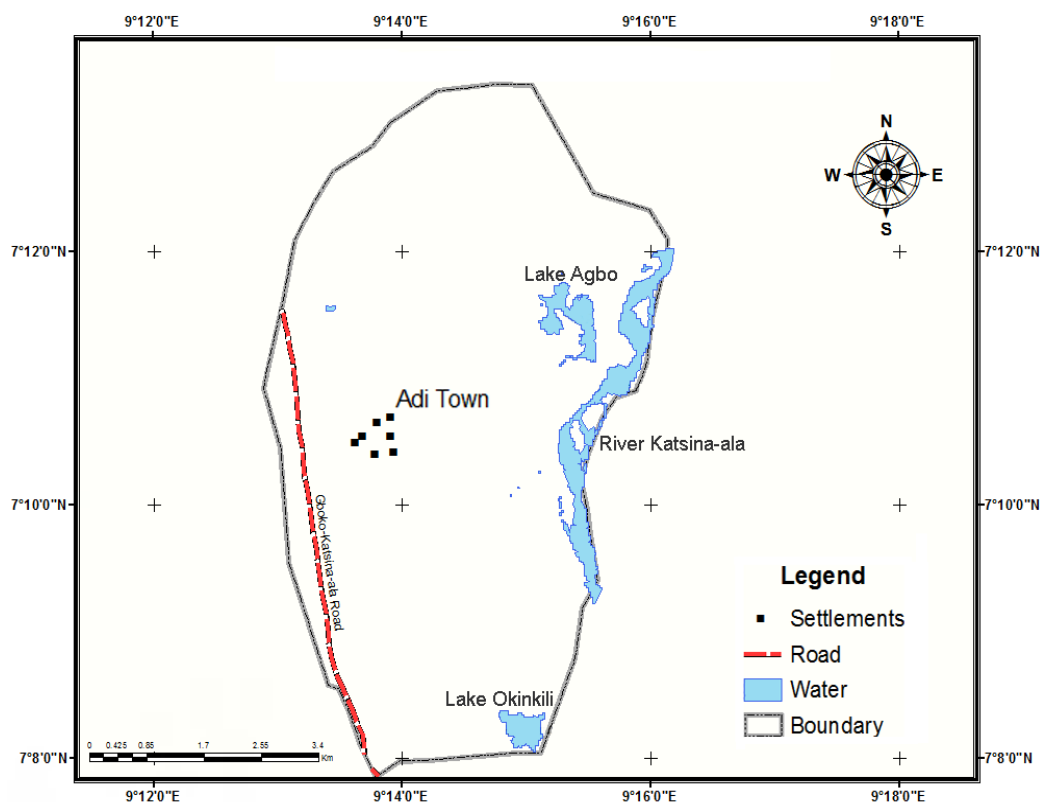
gone changes due to continuous clearing for cropping. Increasing population growth, bush-burning practices, and cattle grazing have all contributed to the alteration of vegetation over time (Hula, 2010).

Figure 1. Adi, Buruku LGA in Benue State and Benue State in Nigeria



Source: GIS Lab, University of Jos, Nigeria.

Figure 2. Adi and Environs



Source: GIS Lab, University of Jos, Nigeria



Data were sourced from both primary and secondary sources. Landsat imagery from 1986 to 2019 was collected at intervals, along with climatic data such as temperature and rainfall, as well as geographic coordinates obtained using GPS. Four Landsat images were acquired from the United States Geological Survey (USGS) for the period between October and December. The images included Multispectral Scanner (MSS) data, initially used for land cover sensing, which was later upgraded to Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+). Details on the spatial, spectral, and metadata attributes of the images are presented in Table 1.

Table 1. Image Metadata

Satellite	Sensor	Date of Acquisition	Spatial Resolution	Path and Row	Cloud Cover	Source
Landsat 4–5	TM	12/12/1986	28.5 m	187/55	1.00	USGS
Landsat 7	ETM+	08/12/1999	30.0 m	187/55	0.09	USGS
Landsat 7	ETM+	19/12/2003	30.0 m	187/55	0.00	USGS
Landsat 8	ETM+	07/12/2019	30.0 m	187/55	0.15	USGS
Admirative/Base map						DaviGIS

Source: USGS, (2019)

Similarly, rainfall and temperature data were obtained from the Akperan Orshi College of Agriculture, Yandev weather station. It is an agro-meteorological station with station number 0709/20, located approximately 29.48 kilometers from Adi. The weather station is situated on moderately undulating land (Tyubee et al., 2020). The distance is considered suitable for analysis with little or no negative impact, taking into account the World Meteorological Organization's guidelines of 10–20 km for undulating terrain in less urbanized areas (Ali, 2018; WMO, 2023). The monthly average records of the climatic parameters were used to determine the relationship between NDVI and climate variables by correlating rainfall and NDVI, as well as temperature and NDVI, using linear regression analysis. The linear regression formula is given by:

$$Y=a+bX_1+bX_2+bX_3- - -b_n x_n +E$$

where:

Y= Dependent variables (NDVI values),

X_1, X_2 and X_3 = Independent variables (Rainfall),

X_1 = Rainfall,

a = Constant showing intercept for regression,

b_1 to b_n = Independent variable coefficient,

E = error term.

To further investigate the major causes of vegetation degradation in the area, a total of 103 questionnaires were distributed. This was particularly important since NDVI values cannot be used to precisely determine the specific human activities affecting the area. A Geographic Positioning System (GPS) was used to obtain the coordinates of the study area boundaries in order to delineate the boundary map (Sadiya & Hasan, 2025). It was also used to record the coordinates of different land

cover types. NDVI was employed for the analysis. NDVI is highly sensitive to the presence, density, and condition of vegetation and is linked to absorbed photosynthetically active radiation (PAR) and vegetation primary production. Chlorophyll, a key pigment in leaves, plays a vital role by absorbing red and blue wavelengths while reflecting green, which is why leaves appear green during the rainy season when chlorophyll levels peak. In contrast, during the dry season, with reduced chlorophyll content, less red light is absorbed and more is reflected, giving leaves a red or yellow appearance (yellow being a blend of red and green light). Additionally, the internal structure of healthy leaves efficiently diffuses and reflects near-infrared wavelengths (Jin et al., 2018b; Y. Li et al., 2016). The NDVI was calculated using the formula:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where:

RED = Spectral reflectance measurements acquired in the red (visible light) region,

NIR = Near-infrared region and NIR representing Band 4 and RED representing Band 3.

NDVI values ranged from -1 to 1, with values close to 1 indicating high, healthy vegetation and those near -1 representing low or no vegetation (Neil-Dunne, 2014). The study employed supervised classification to categorize land uses, including vegetated areas, water bodies, agricultural land, and bare soil. A pixel-based training approach was employed. Each training sample was labelled using data from Geographic Positioning System (GPS) collected in the field. NDVI values derived from satellite images were reclassified using ILWIS 3.8.6 software and analysed in ArcGIS 10.3.1 for area calculations and temporal comparisons. Areas with high NDVI and no NDVI were calculated in ArcGIS using the raster calculator. Climatic data, such as rainfall and vegetation, were compared with NDVI using linear regression, highlighting areas with significant changes. Results were visualized through maps, tables, and graphs, while questionnaire data were analysed using SPSS to identify non-climatic factors contributing to vegetation loss. Findings are presented in graphs and tables for clarity.

Classification Accuracy Assessment

The classification was performed using supervised maximum likelihood classification (MLC) with field-based GPS training data and was validated visually using NDVI overlays and land use pattern interpretation over time. Using 100 random validation points across the five land cover classes of Adi, the following confusion matrix (in % of points classified) was derived (Table 2).

An accuracy of 88% and a Kappa coefficient of 0.79 suggest a strong agreement between the classified results and the expected ground truth, indicating high classification reliability. The use of supervised classification, validated GPS training sites, and NDVI cross-checks further supports the robustness of the classification results.

Table 2. Confusion Matrix (in % of points classified)³

Reference \ Classified	High Vegetation	Agriculture	Built-up	Water Body	Bare Land	Row Total
High Vegetation	18	2	0	0	0	20
Agriculture	3	32	2	0	1	38
Built-up	0	1	18	0	1	20
Water Body	0	0	0	10	0	10
Bare Land	0	1	1	0	10	12
Column Total	21	36	21	10	12	100

RESULTS

Vegetation Analysis

The state and changes in vegetation were assessed using NDVI for the study area at intervals in 1986, 1999, and 2019. Between the months of October and December, the region experienced the highest amount of rainfall during the second rainfall semester (Adamgbe & Ujoh, 2012b). NDVI values were calculated using a simple summation formula. Landsat 7 (28.5 m resolution) and Landsat 8 (30 m resolution) were adjusted by multiplying their pixel values by 28.5 and 30, respectively, to harmonize the data.

Figure 3. NDVI of Adi in the year 1986 (a); Land-use Classification (LUC) of Adi in 1986 (b)

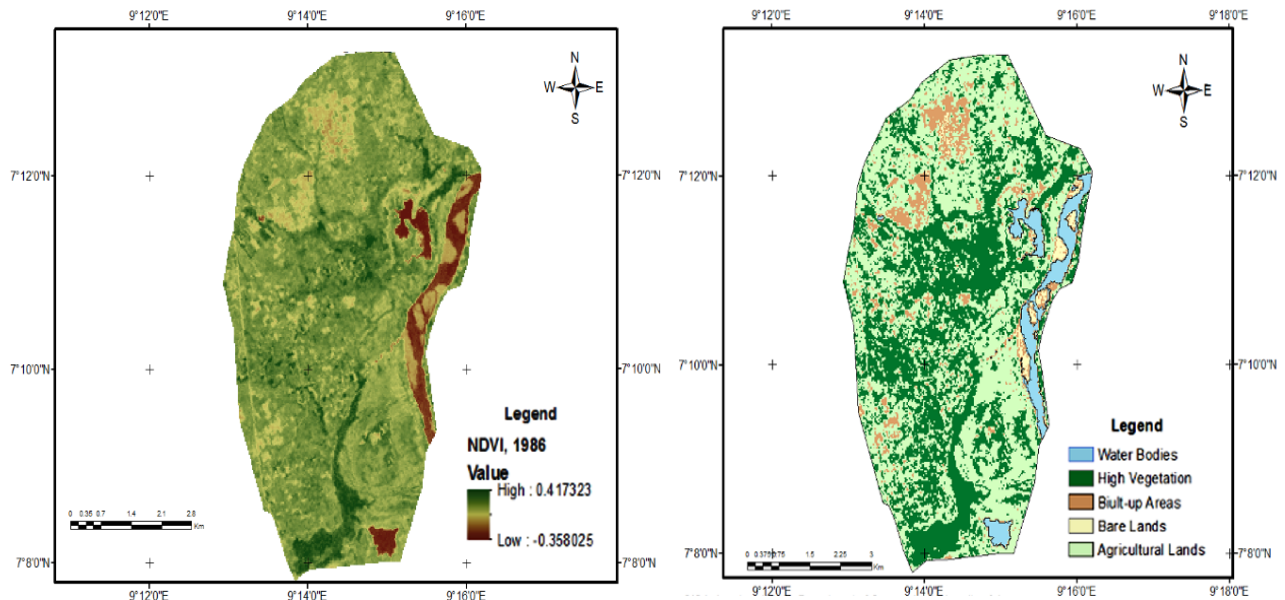


Table 3 presents the land use classification of Adi in 1986. The total land area was categorized into five classes: agricultural land, high vegetation, built-up areas, water bodies, and bare land. Agricultural land was the dominant category, covering 718,399.5 square meters, which accounted for 48.33% of the

³ Accuracy Metrics: • Overall Accuracy (OA): 88%, • Producer's Accuracy (PA): *High Vegetation*: 85.7%, *Agriculture*: 88.9%, *Built-up*: 85.7%, *Water Body*: 100.0%, *Bare Land*: 83.3%, • User's Accuracy (UA): *High Vegetation*: 90.0%, *Agriculture*: 84.2%, *Built-up*: 90.0%, *Water Body*: 100.0%, *Bare Land*: 83.3%, • Kappa Coefficient (K): 0.7

total area. This highlights the prominence of agriculture in the region, likely serving as the primary livelihood for the local population. High vegetation, the second-largest category, occupied 575,044.5 square meters, representing 38.69% of the total area. This significant vegetative cover reflects the ecological richness of the landscape at the time.

Table 3. Distribution of LUC of 1986

Class of Land cover	Cummulative Pixel Values	Area (m ²)	Area (acres)	Percent %
Water	2525	71962.50	17.78	4.84
High Vegetation	20177	575044.50	142.05	38.67
Agricultural Lands	25207	718399.50	177.50	48.33
Bare Lands	709	20206.50	4.99	1.36
Built-up Areas	3535	100747.50	24.90	6.78
<i>Total</i>		<i>1486361</i>	<i>367.22</i>	<i>100</i>

Built-up areas, encompassing 100,747.5 square meters, or 6.78% of the total area, reflected the early stages of urbanization and infrastructural development in the region. Water bodies, covering 71,962.5 square meters (4.84% of the land area), indicated the presence of rivers, lakes, or reservoirs, which likely played a crucial role in supporting both agriculture and local ecosystems. Bare land was the smallest category, comprising just 20,206.5 square meters, or 1.36% of the total area, suggesting limited areas of exposed soil or land degradation. The land use distribution in 1986 depicted a predominantly agrarian landscape with extensive vegetative cover and minimal urbanization or bare land. This baseline reflects a relatively stable and ecologically balanced environment, providing a critical context for understanding subsequent changes in land use (Figure 3–4).

Figure 4. Land-Use Classification (LUC) in Adi, 1986

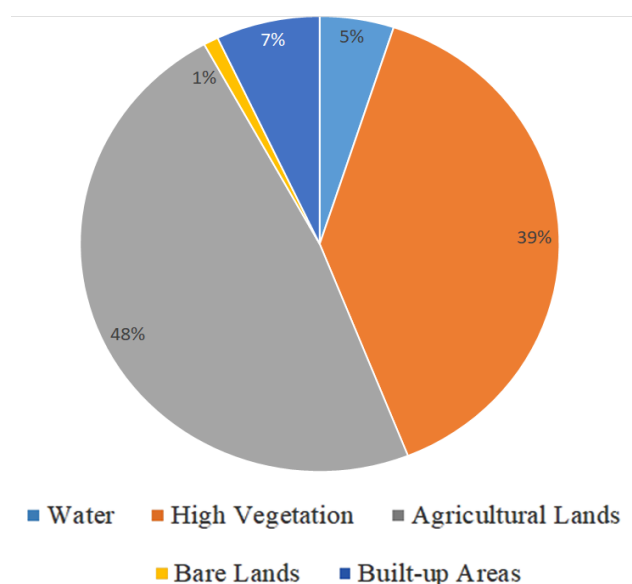
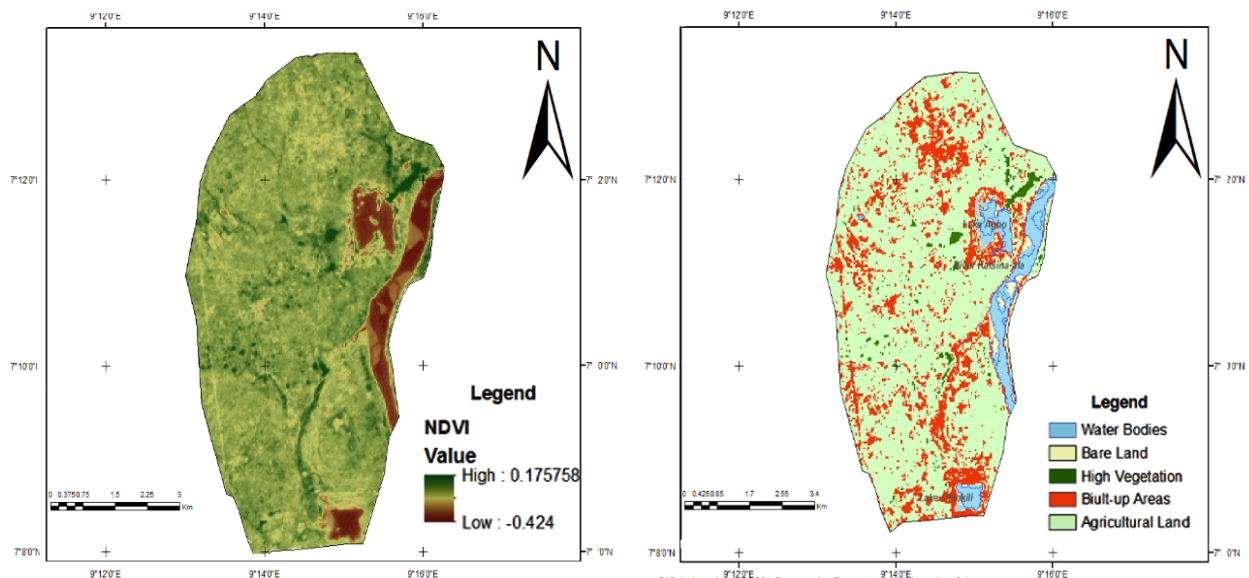


Table 4 presents the land use classification of Adi in 1999, covering a period of 13 years. This revealed significant changes compared to the 1986 data. The total land area was again classified



into five categories: agricultural land, high vegetation, built-up areas, water bodies, and bare land. Agricultural land remained the dominant land cover, increasing significantly to 998,430 square meters, which accounted for 70.69% of the total area. This notable growth highlights the continued and expanding reliance on agriculture, driven by population growth and the intensification of farming activities. Built-up areas experienced substantial growth, covering 282,060 square meters, or 19.97% of the total area. This sharp increase in urban and infrastructural development reflects rapid urbanization during this period (Figure 5).

Figure 5. NDVI of Adi in the year 1999 (a); Land-use Classification (LUC) of Adi in 1999 (b)



Water bodies also expanded slightly, occupying 80,730 square meters, which represented 5.72% of the total area. In contrast, high vegetation underwent a dramatic decline, shrinking to just 24,030 square meters, or 1.70% of the total area. This reduction reflects widespread deforestation or vegetation loss, linked to agricultural expansion and urban development. Bare land also increased marginally to 27,240 square meters, comprising 1.93% of the total area, indicating a slight rise in exposed or degraded land. The land use distribution in 1999 showed a landscape dominated by agricultural land, with significant growth in built-up areas and water bodies, alongside a pronounced decline in high vegetation. These changes underscore the impacts of human activity on the environment, characterized by urbanization, deforestation, and agricultural expansion, which reshaped the region's ecological and land use dynamics.

During this period, high vegetation significantly decreased to 24,030 m², making up only 1.70% of the area—a reduction of 36.99%. Water bodies increased to 5.72%, while bare surfaces accounted for 1.93%. The sharp decline in high vegetation was attributed to population growth and the expansion of built-up areas, which placed increasing pressure on the land (Figure 6).

Table 4. Distribution of Land-use Classification (LUC) of 1999

Class of Land Cover	Pixel Value	Area (m ²)	Area (acres)	Percent %
Water	2691	80730	19.95	5.72
High Vegetation	801	24030	5.94	1.70
Agricultural Lands	33281	998430	246.72	70.69
Bare Lands	908	27240	6.73	1.93
Built-up areas	9402	282060	69.72	19.97
<i>Total</i>		<i>1412490</i>	<i>349.06</i>	<i>100</i>

Figure 6. Land-Use Classification (LUC) in Adi, 1999

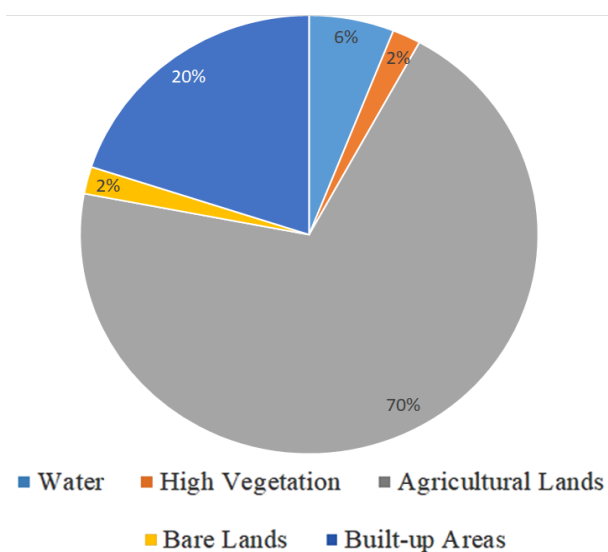
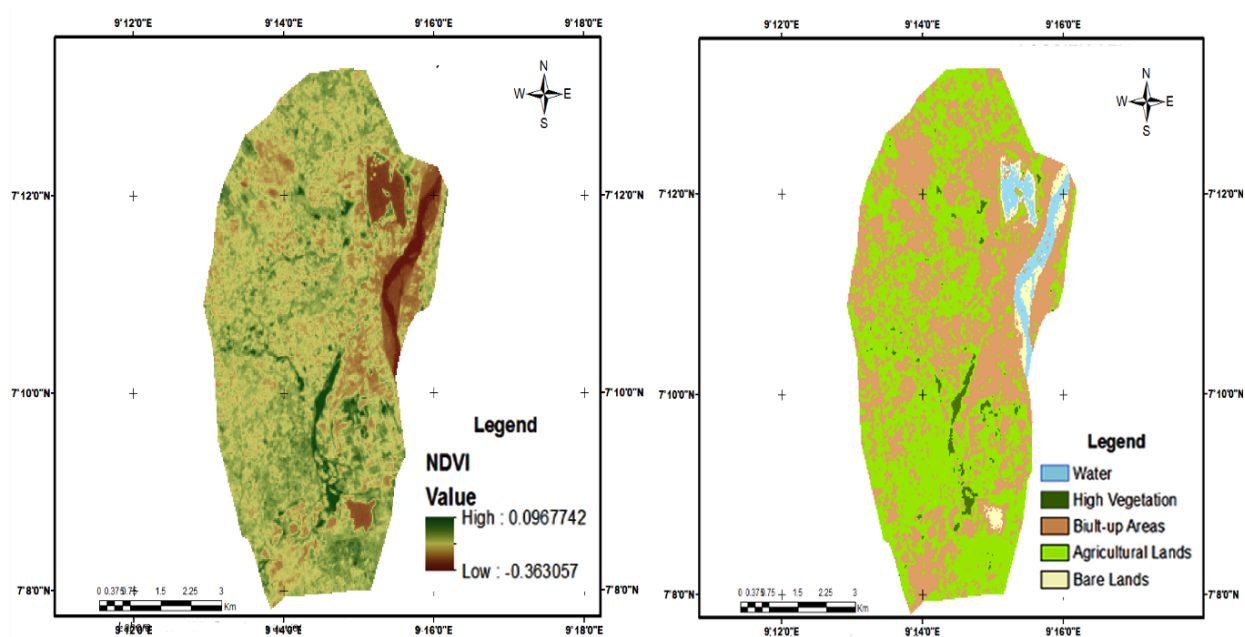


Figure 7. NDVI of Adi in the year 2003 (a); Land-use Classification (LUC) of Adi in 2003 (b)





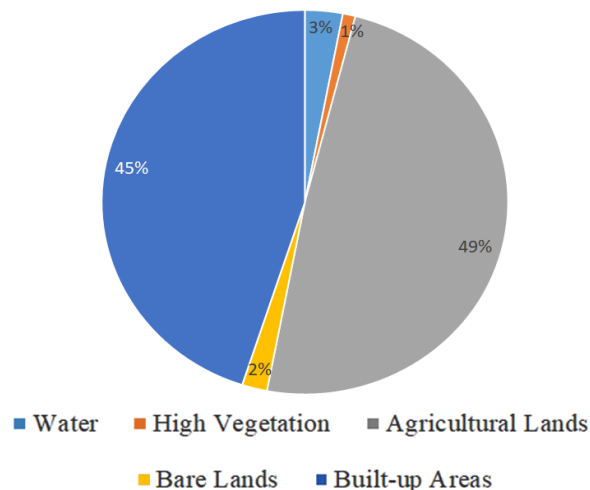
In 2003, the land use reclassification revealed significant human intervention and development in the region. Agricultural land remained the largest land cover, accounting for 680,250 square meters, or 48.58% of the total area. While still dominant, this represented a notable decrease from 70.69% in 1999, suggesting a reduction in farming areas, possibly due to urban expansion (Figure 7).

Table 5. Distribution of Land-use Classification (LUC) of 2003

Class of Land Cover	Pixel Value	Area (m ²)	Area (acres)	Percent %
Water	1520	45600	11.27	3.26
High Vegetation	625	18750	4.63	1.34
Agricultural Lands	22675	680250	168.03	48.58
Bare Lands	1040	31200	7.71	2.23
Built-up areas	20814	624420	154.33	44.59
<i>Total</i>		<i>1400220</i>	<i>345.97</i>	<i>100</i>

Built-up areas experienced a dramatic increase, covering 624,420 square meters, which accounted for 44.59% of the total area. This sharp growth reflects significant urbanization and infrastructural development, driven by population growth and economic activities. Water bodies decreased slightly to 45,600 square meters, representing 3.26% of the total area (Table 5, Figure 8). This decline indicates reduced water availability and shifting land use priorities.

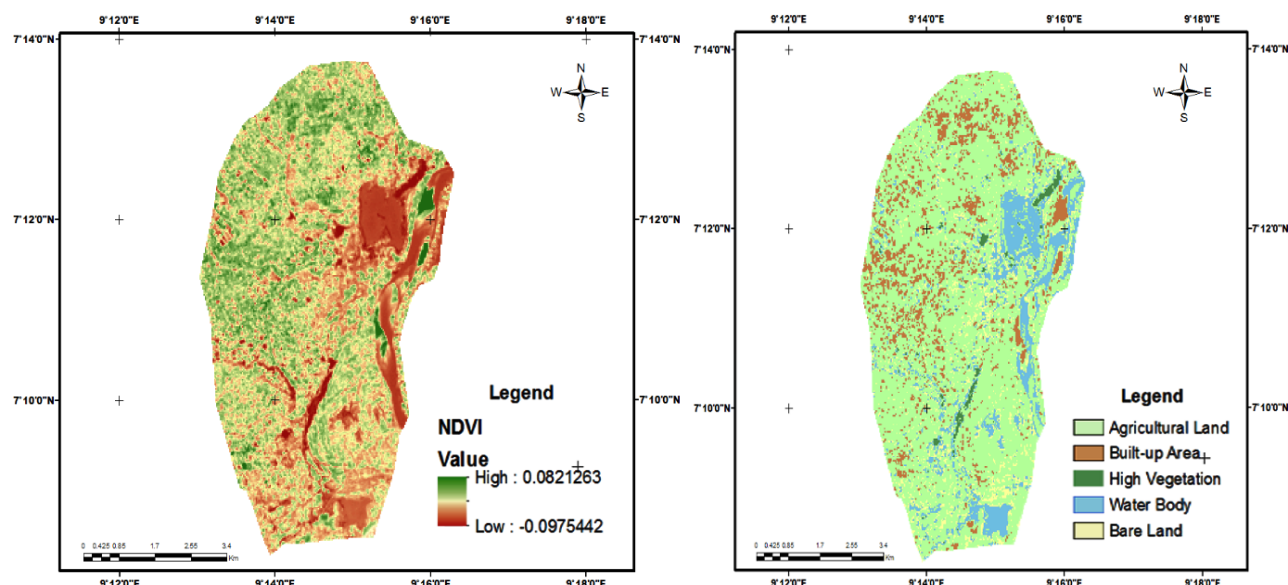
Figure 8. Land-Use Classification (LUC) in Adi, 2003



High vegetation continued to decline, shrinking further to just 18,750 square meters, or 1.34% of the total area. This reduction reflects the persistent loss of natural vegetation, linked to the expansion of built-up areas and agricultural practices. Bare land increased modestly to 31,200 square meters, making up 2.23% of the total area. This suggests a gradual rise in land degradation and the possibility that some areas were left fallow. The land use distribution in 2003 indicated a landscape increasingly shaped by urbanization, as built-up areas expanded significantly at the expense of agricultural land

and high vegetation. These changes reflect the intensifying human impact on the area, characterized by deforestation, reduced vegetation, and a growing urban footprint.

Figure 9. NDVI of Adi in 2019 (a); LUC of Adi in 2019 (b)



In 2019, the NDVI index showed an inverse pattern, with urban areas recording the highest value of 0.0821, while highly vegetated landmasses registered a negative value of -0.0974 . This represents a significant contrast compared to the 2003 data (Figure 9, Table 6).

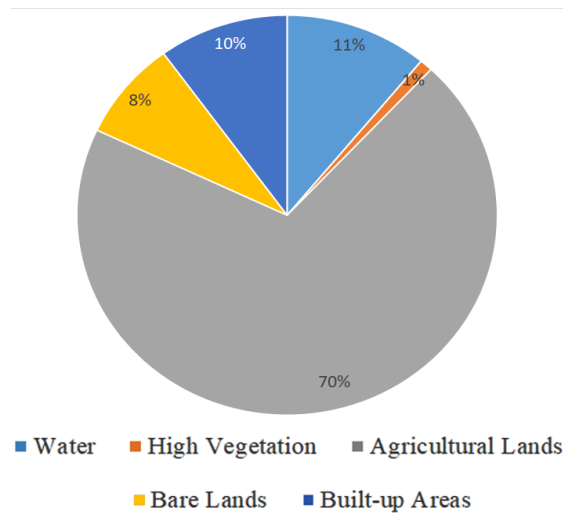
Table 6. Distribution of Land-use Classification (LUC) in 2019

Class of Land cover	Pixel Value	Area (m ²)	Area (acres)	Percent %
Water	5255	157650	38.96	11.27
High Vegetation	470	14100	3.49	1.01
Agricultural Lands	32559	976770	241.39	69.81
Bare Lands	3722	111660	27.6	7.98
Built-up areas	4634	139020	34.35	9.94
<i>Total</i>		<i>1399200</i>	<i>345.79</i>	<i>100.00</i>

The Land-Use Classification (LUC) in 2019 showed an increase in agricultural land, which covered 69.81% of the area (976,770 m²). Water bodies accounted for 11.27% (157,650 m²), followed by built-up areas at 9.94% (139,020 m²), and bare land at 7.98% (111,660 m²). High vegetation decreased, representing only 1.01% (14,100 m²), due to urbanization and the expansion of agriculture to meet the needs of the growing population (Figure 10).

The presence of vegetation around the built-up areas is noticeable; this is due to the practice of orchard farming within and around these areas, as confirmed by a reconnaissance survey. These patches of vegetation within urban zones may have obscured some structures, leading to a reduction in the apparent size of urban land in the 2019 NDVI analysis.

Figure 10. Land-Use Classification (LUC) in Adi, 2019



Vegetation Trend of Adi Between 1986 and 2019

There has been a significant change in the vegetation of Adi from 1986 to 2019. During this period, the land-use trend revealed substantial shifts in the allocation of land among various categories. Water bodies experienced fluctuations, initially covering 4.84% of the area in 1986, slightly increasing to 5.72% in 1999, decreasing to 3.26% in 2003, and then surging to 11.27% by 2019, indicating improved water management or the expansion of aquatic systems. High vegetation underwent a dramatic decline, dropping from 38.69% in 1986 to 1.70% in 1999, further decreasing to 1.34% in 2003, and reaching only 1.01% in 2019, signaling extensive deforestation or land clearing. Agricultural land exhibited considerable variability: it occupied 48.33% of the area in 1986, increased to 70.69% in 1999, decreased to 48.58% in 2003, and rose again to 69.81% by 2019. This reflects ongoing agricultural expansion and land-use prioritization. Bare land showed a steady increase, from 1.36% in 1986 to 1.93% in 1999, 2.23% in 2003, and 7.98% in 2019, likely indicating land degradation or abandonment.

Built-up areas expanded significantly between 1986 and 2003, growing from 6.78% to 44.59%, but declined sharply to 9.94% by 2019, suggesting shifts in urbanization patterns or reclassification of land use. The findings indicate the intensification of agriculture, significant reductions in natural vegetation, and dynamic changes in water and urban land use over the decades (Table 7; Figure 11–12).

Table 7. Land-Use Classification (LUC) Trend Between 1986 and 2003 (%)

Year	1986	1999	2003	2019
Water	4.84	5.72	3.26	11.27
High Vegetation	38.69	1.70	1.34	1.00
Agricultural Land	48.33	70.69	48.58	69.81
Bare Land	1.36	1.93	2.23	7.98
Built-up Area	6.78	19.97	44.59	9.94
<i>Total</i>	<i>100</i>	<i>100</i>	<i>100</i>	<i>100</i>



Figure 11. Land-Use Classification (LUC) Trend in Adi, 1986–2019

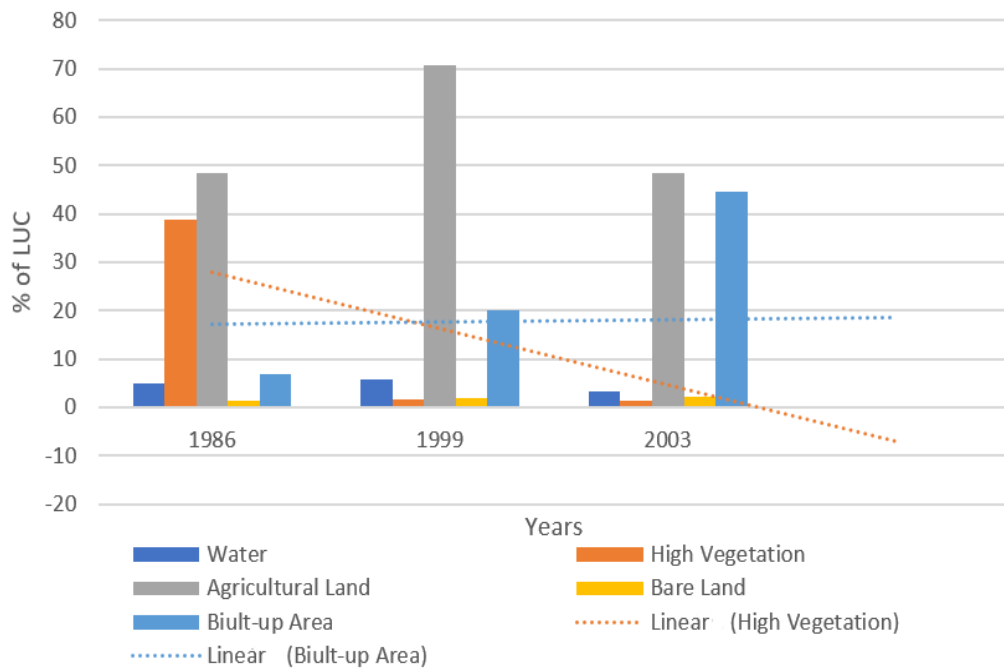
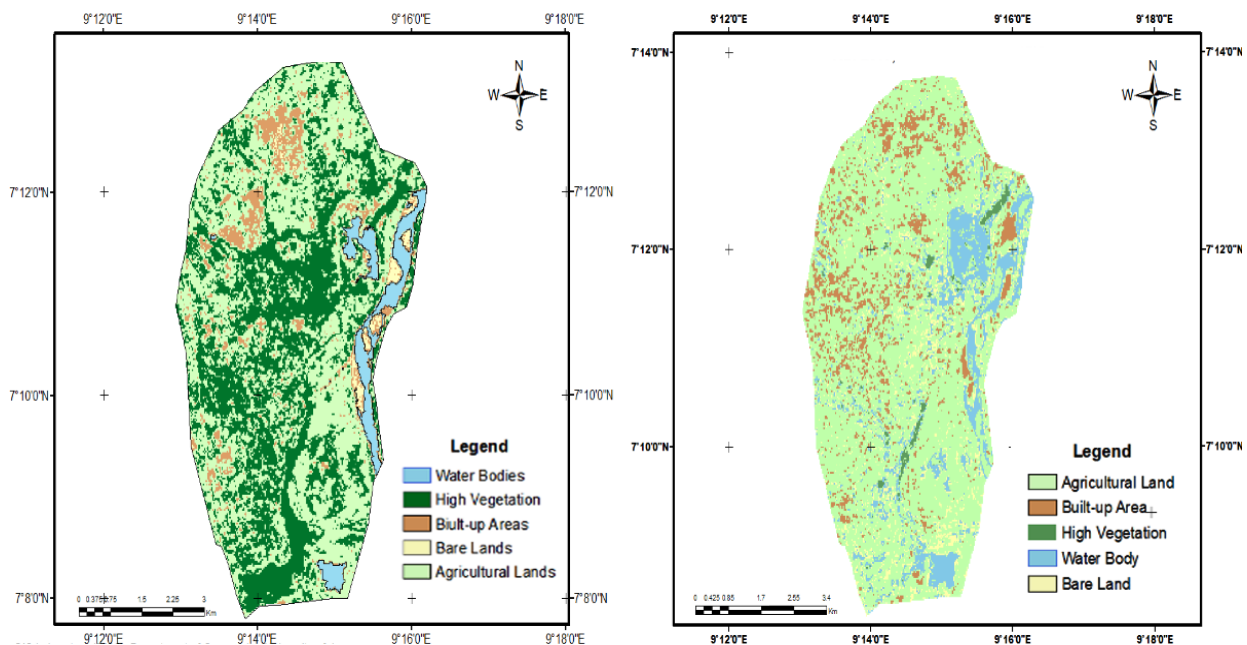


Figure 12. Comparison Between 1986 (a) and 2019 (b) LUC From Satellite Imageries



Driving Factors of the Trends in Vegetation Change

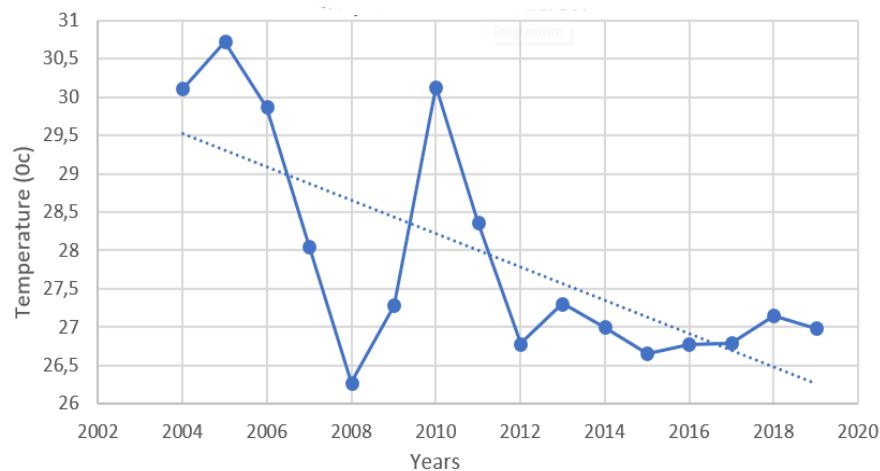
The NDVI analysis revealed a significant decline in vegetation, decreasing from 38.69% to 1.01%—a difference of 37.68%. This suggests that much of the forested land has been converted to agricultural use. However, the NDVI alone does not indicate whether climate factors were responsible for this

degradation, even though climate is a key determinant of vegetation health. Moreover, it does not account for the specific human activities that contributed to vegetation loss. To address this limitation, a climate analysis of the area was conducted, and questionnaires were administered to better understand the underlying causes.

Relationship Between Vegetation Degradation and Temperature in Adi

Graphical analysis showed a decrease in temperature over time, with the maximum temperature dropping from 30.11°C in 2004 to 26.98°C in 2019. However, temperature variation is unlikely to be responsible for the vegetation decline in this context, as temperature is not typically a limiting factor for vegetation in tropical regions (Odenkunle, 2004). Temperature is also not a reliable indicator of energy for potential evapotranspiration, as it lags behind solar radiation. Moreover, seasonal temperature variation in the tropics is minimal, allowing a wide range of crops to thrive under varying thermal conditions (Odenkunle, 2004). The minimum and maximum temperature thresholds for most tropical plants in Nigeria are 6°C and 40°C, respectively (Ayoade, 2004), indicating that these slight temperature fluctuations remain conducive to plant growth—unlike in regions of high relief (Schmid et al., 2018; Figure 13).

Figure 13. Yearly Average Temperature Variation



Relationship Between Vegetation Degradation and Precipitation in Adi

There is a significant link between vegetation and precipitation. Precipitation is considered the most limiting factor in arid and semi-arid zones (Zerkani et al., 2022). Although various factors—including atmospheric conditions, topography, and land cover types—can influence patterns of change (Soomro et al., 2021). For instance, interannual variations in precipitation play a significant role in shaping vegetation responses, as precipitation is crucial in driving vegetation activity. The magnitude, intensity, and distribution of precipitation strongly influence these patterns and the associated vegetation dynamics (Soomro et al., 2021; Weiss et al., 2004). To determine the impact of precipitation on vegetation degradation in Adi, a regression analysis of rainfall against NDVI was conducted (Figure 14).

Figure 14. Rainfall between 1986 and 2019

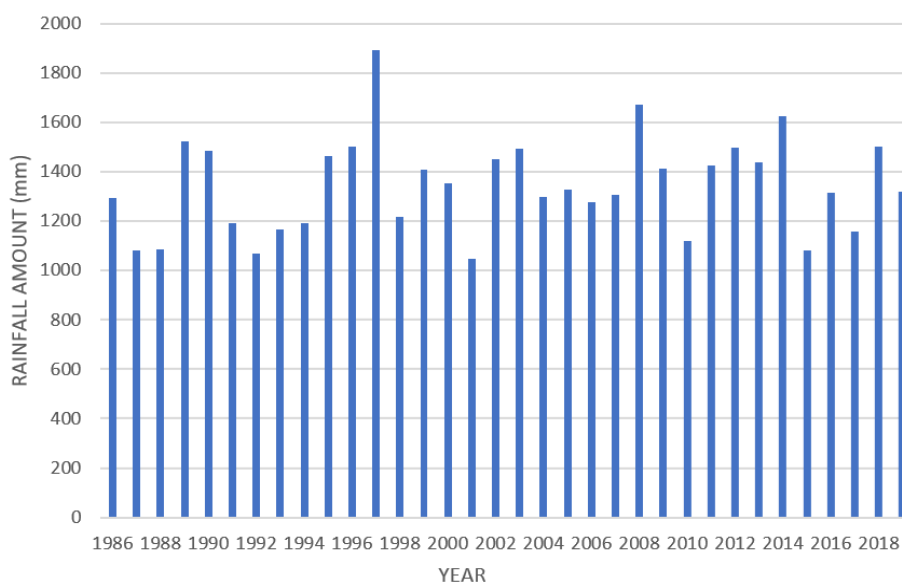


Table 8. Regression Analysis of NDVI Against Rainfall

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.531	0.282	-0.077	288513.9957	1.496

Figure 15. Regression of NDVI and Rainfall

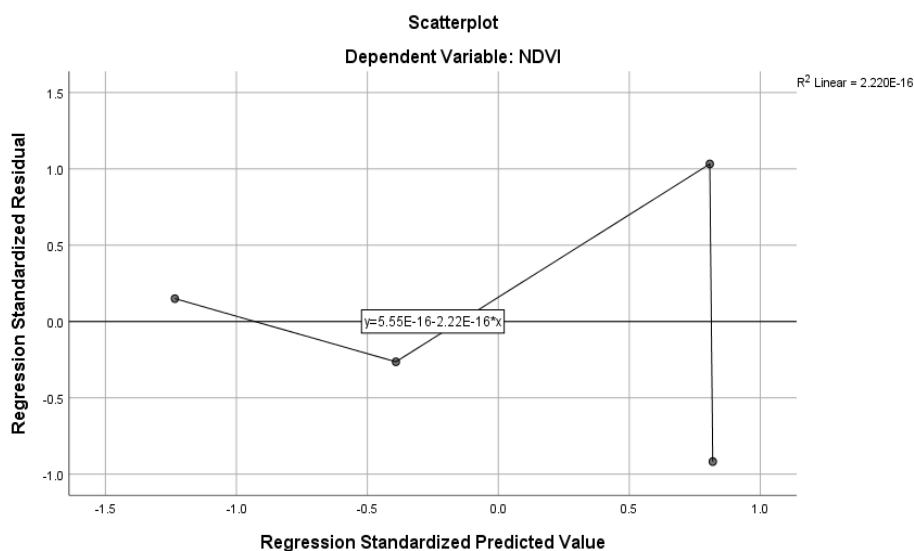


Table 9. Model Summary of the Regression Analysis

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin Watson
.531 ^a	0.282	-0.077	288513.9957	1.496

a. Predictors: (Constant), Rainfall; b. Dependent Variable: NDVI



The regression analysis between the NDVI (Normalized Difference Vegetation Index) and rainfall revealed a moderate positive correlation, with an R value of 0.531, suggesting a relatively weak relationship between the two variables. However, the R-squared value of 0.282 indicated that 28.2% of the variability in NDVI can be explained by rainfall, while the remaining 71.8% may be attributed to other factors such as temperature, soil conditions, or human activities (Table 8–9; Figure 15 –16).

Table 10. Coefficient Summary of the Regression Analysis

Rainfall	Unstandardized coefficients		Unstandardized coefficients	t	sig
	B	Std Error	Beta		
	2242050.1	2353989.59			
	-1518.613	1712.074	-0.531	-0.887	0.469

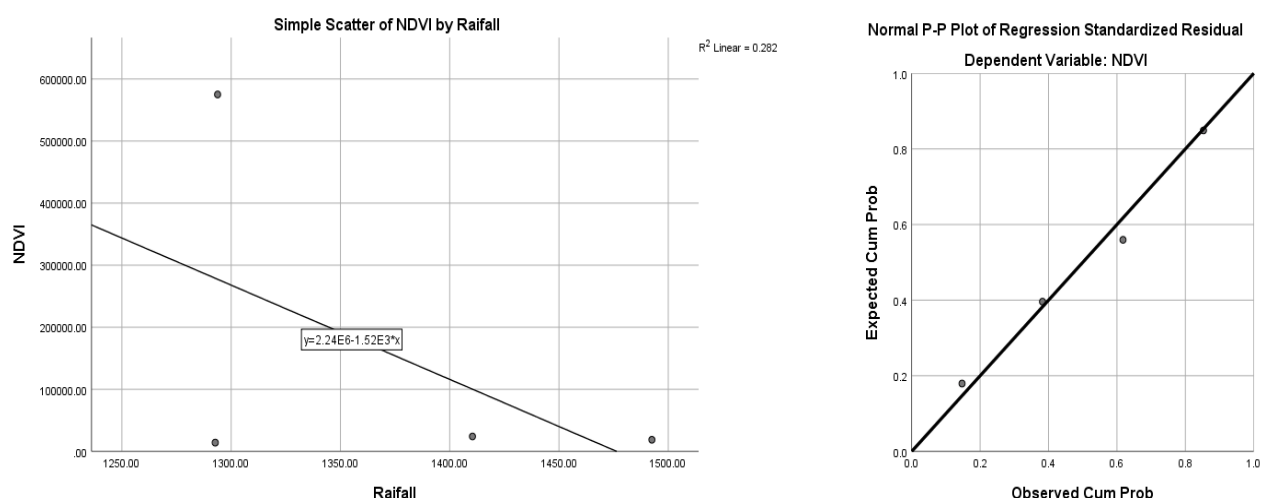
Table 10 presents a summary of the impacts of rainfall on vegetation in the study area. NDVI values of vegetation were used as the dependent variable, while rainfall and the years under review served as the independent variables. A bivariate regression was conducted to examine how overall rainfall could predict the integrated NDVI in the area. A scatter plot showed that the relationship between rainfall and NDVI was negative and linear, and it did not reveal any bivariate outliers. The correlation between rainfall and integrated NDVI was not statistically significant, with $b = -0.53$, $t(0.5)$, $p = 0.441$. The regression equation is given by: $Y = 2,242,050.09 - 1,518.613X$.

Table 11. Residual Statistics Summary

Statistic	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	-24480.2637	278938.688	157981.125	147751.137	4
Residual	-264838.688	297776.313	0	235570.691	4
Std. Predicted Value	-1.235	0.819	0	1	4
Std. Residual	-0.918	1.032	0	0.816	4

The R^2 value for the resulting equation was 0.282, indicating that 28.2% of the variation in NDVI can be predicted from rainfall. This suggests a positive but weak relationship. A 95.5% confidence level was used. The slope estimated the NDVI based on the range of rainfall. Thus, for each unit increase in rainfall, NDVI decreases by a standard deviation of –531 in rainfall amounts (Table 11).

Figure 16. Simple Scatter of NDVI by Rainfall (a);
Observed and Expected Cumulative Probability Residuals of NDVI by Rainfall (b)



Human Activities Affecting Vegetation in Adi

Findings from the study show how human activities contributed to vegetation degradation in Adi. Table 12 presents the distribution of various domestic fuel options used by residents for cooking. A total of 87 people, representing 84.5% of the respondents, used fuelwood for cooking, while only 5.8%, 2.9%, and 3.9% used kerosene, gas, and other forms of fuel, respectively. This amounts to 16% of respondents using alternatives to fuelwood. This finding aligns with studies conducted in other regions, which show that fuelwood collection is one of the major contributors to vegetation loss in many parts of Nigeria (Ebenezer, 2015).

Table 13 shows the farming practices engaged in by the people. The results indicate that 58 respondents, representing 61.1%, practice continuous farming on the same piece of land year in and year out. Reports from the respondents revealed that some plots of land are cultivated up to three times within a single year.

Table 12. Practices Affecting Vegetation

Source of Fuel	Frequency	Percent
Fuel wood	87	87
Kerosene	6	6
Gas	3	3
Others	4	4
<i>Total (Valid)</i>	<i>100</i>	<i>100</i>

Table 13. Distribution of Farming Practices in Adi

Farming Practice	Frequency	Percent
Crop Rotation	58	61.1
Shifting Cultivation	34	35.8
Bush Fallowing	3	3.2
<i>Total</i>	<i>95</i>	<i>100</i>

Thirty-five point eight percent of respondents practice shifting cultivation, while 3.2% practice the fallowing system. Intensive cultivation depletes plant species in an area, creating opportunities for bare land. These results are consistent with those of Jibril et al. (2015).

Table 14 illustrates the distribution of land preparation methods among respondents. Bush burning emerged as the most prevalent method, adopted by 51 respondents (49.5% of total responses and 52.6% of valid responses). Mulching was the second most common method, chosen by 29% of respondents. Compost manure, the least favored method, was used by 18.6% of respondents. The findings indicate a preference for traditional methods, especially bush burning, despite its environmental implications. Table 15 summarizes people's perceptions of the impacts of urban expansion on vegetation in the study area. A total of 65.3% agreed that there has been growth in settlements in the study area, while 34.7% disagreed.

Table 14. Preparatory Methods

Land Preparation Methods	Frequency	Percent
Bush Burning	51	52.6
Mulching	28	28.9
Compost Manure	18	18.6
<i>Total</i>	<i>97</i>	<i>100,0</i>

Table 15. Perception of Urban Growth Impact on Vegetation

Perception	Frequency	Percent
Strongly Agree	38	37.6
Agree	28	27.7
Disagree	19	18.8
Strongly Disagree	16	15.8
<i>Total</i>	<i>101</i>	<i>100,0</i>

CONCLUSIONS

The analysis of the NDVI data revealed significant vegetation degradation in the area, amounting to approximately 37.68%. While temperature did not appear to directly contribute to this decline, rainfall and human activities were identified as the primary drivers of vegetation loss. The regression analysis showed a significant relationship between rainfall and integrated NDVI, indicating that rainfall variability plays a substantial role in vegetation dynamics. Additionally, descriptive statistics highlighted that human activities—including agricultural practices, brick-making, urbanization, fuelwood collection, bush burning, pastoralism, and logging—have significantly accelerated vegetation degradation in the Adi region.

Activities in Adi are not sustainable, as the majority of residents rely on fuelwood (84.5%) and fossil fuels (6%) for energy, rather than adopting eco-friendly alternatives such as solar power. This contradicts UN-Habitat's vision of making cities inclusive, safe, resilient, and sustainable (UN-Habitat,

2018). Models such as smart cities promote environmental sustainability through clean energy use and reduced dependence on fossil fuels (Allam et al., 2022; Benini et al., 2024). Such dependence on non-renewable and polluting energy sources contradicts the principles of sustainable urban development, which advocate reducing fossil fuel use, protecting natural habitats, and integrating green spaces within urban areas. These practices highlight the urgent need for sustainable energy policies and infrastructure.

It is clear that sustainable urbanism, particularly in the context of Adi, should be understood as urban development that minimally disrupts biodiversity while supporting the preservation of the Earth's ecosystems. It should involve transitioning from conventional energy sources to modern, renewable alternatives such as solar and hydropower. By embracing digital technologies and data-driven systems, Adi can enhance the efficiency of city management, especially in areas such as transportation, resource utilization, and energy consumption. By adopting this approach, Adi can become a model for smart, environmentally responsible urban development.

To address these challenges, the following measures are recommended. First, the government should initiate extensive public awareness campaigns to educate communities about the importance of vegetation and its critical role in sustaining both human well-being and environmental health. These campaigns should emphasize the long-term consequences of vegetation loss and the benefits of sustainable practices.

Second, policies such as “Green the Land” should be implemented to promote large-scale afforestation of degraded areas. This initiative could be supported by offering incentives to individuals and organizations that comply with environmental policies, while enacting strict penalties for violators. Afforestation efforts will not only restore degraded lands but also contribute to sustainable urban development.

Third, the government should prioritize investment in agricultural innovation by developing improved crop varieties that produce high yields on smaller land areas. This approach would help ensure food security for the growing population while minimizing the need to expand agricultural land, thereby reducing pressure on natural vegetation.

Fourth, the establishment of additional meteorological stations at close intervals is crucial. These stations should be equipped with automated systems and staffed by trained personnel to monitor climatic and weather elements effectively. The data collected should be made readily accessible to researchers, enabling more accurate analysis and informed decision-making.

Finally, urgent and effective measures must be adopted to mitigate the impacts of climate change on the environment. This includes implementing strategies to build resilience to climate variability, enhancing environmental conservation, and fostering sustainable practices to ensure long-term ecological balance.

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Morphometric Response to Channel Avulsion in the Mahananda River Basin: A Comparative Analysis of Pre- and Post-Abandonment Watersheds Across Nepal, India, and Bangladesh

ABSTRACT

Channel avulsion plays a critical role in shaping alluvial river systems, yet its morphometric and tectonic consequences remain underexplored in transboundary basins. This study assesses the morphometric response to a historical avulsion event in the lower Mahananda River Basin, spanning Nepal, India, and Bangladesh. Using georeferenced historical maps (1928, 1974), multi-resolution DEMs (SRTM and ALOS PALSAR), and hydrological modeling in ArcGIS Pro, we delineated three watershed units: the Old Mahananda Basin (OMB), the Current Mahananda Watershed (CMW), and the Abandoned Mahananda Watershed (AMW). A detailed morphometric comparison across linear, areal, relief, and tectonic indices reveals significant divergence post-avulsion. AMW exhibits an approximately 45% reduction in total stream length, lower drainage density (0.34 km/km²), and diminished relief energy, indicating hydromorphological degradation. In contrast, CMW maintains high fluvial activity, with a greater dissection index and slope variability. Tectonic asymmetry indicators—Asymmetry Factor (AF) and Transverse Topographic Symmetry Factor (TTSF)—suggest lateral tilting toward the east, likely influencing the channel's relocation. Statistical analyses—including Principal Component Analysis (PCA), hierarchical clustering, and correlation heatmaps—identified drainage density, stream frequency, and hypsometric integral as key drivers of post-avulsion differentiation. Custom visualizations further confirmed distinct morphometric regimes across the three sub-watersheds. The integrated approach—merging GIS-based delineation with Python-assisted statistical modeling—offers a replicable framework for assessing avulsion-driven watershed transformation in tectonically sensitive alluvial plains. These findings contribute to a deeper understanding of geomorphic divergence and provide actionable insights for transboundary water resource planning and climate-adaptive land management.

Keywords: channel avulsion, morphometric analysis, Mahananda River Watersheds, tectonic controls, GIS, Python-based modeling

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INTRODUCTION

The term “morphometric” originates from the Greek word “Morphe,” which signifies “shape” or “form,” and “Metrica,” which denotes “measuring” (Gupta et al., 2018; Reyment, 2010). Morphometric analysis can illustrate the relationship between drainage basin geomorphological features and hydraulic parameters, as it entails the mathematical analysis and quantification of the shape, size, and configuration of the Earth’s surface and its landforms (Clark, 1966; Rai et al., 2017; Milutinović, 2021). This approach plays a significant role in understanding the geomorphological features of drainage basins (Rai et al., 2017; Devrani et al., 2022). Horton introduced a conventional method of morphometric analysis to investigate the origins of river networks (Horton, 1932; Horton, 1945). Strahler later modified this method by introducing a new technique for assigning order numbers to channels (Strahler, 1957). Further refinements were made by others, such as Scheidegger (1965) and Shreve (1966).

Morphometric studies in large transboundary tropical basins, like the Congo, illustrate the utility of GIS tools in hydrological understanding (Sibanda et al., 2022). By the end of the 20th century, one million people were using GIS efficiently. Recently, GIS and remote sensing have been effectively used to study river morphology and lithology in the Congo River Basin, revealing erosion-driven changes and sediment dynamics (Mukulia et al., 2024). Complementing GIS and remote sensing approaches, controlled flume experiments have also demonstrated how climate-driven discharge changes influence channel morphology, as seen in the Lower Drava River (Gashi et al., 2023). While GIS systems were established worldwide in the 1950s, the scientific study of landforms—particularly their detection, classification, and morphometric analysis using digital tools—intensified in the 1960s and 1970s. With high-speed processors, new satellite sensors, GPS, and internet-based geo-referenced data collection and transfer, this technology became widespread in the 1980s and 1990s (Anish, 2021). Open-source and commercial GIS software, along with openly accessible high-resolution satellite imagery, have made drainage morphometric analysis easier, faster, and more accurate (Gupta, 2003).

Morphometric analysis of a river basin provides a quantitative description of the drainage system, which is an important aspect of the basins (Strahler, 1964). There are three key aspects mainly used for analysing drainage basin characteristics: linear, areal, and relief aspects, which include stream order, stream length, bifurcation ratio, drainage density, stream frequency, form factor, etc. (Shreve, 1966). The utilisation of GIS for quantitative analysis of morphometric parameters has proven to be highly beneficial in assessing river basins, prioritising watersheds for soil and water conservation, and managing natural resources at a small scale (Vijith, 2006). The application of GIS in morphometric analysis has facilitated our comprehension of many terrain characteristics, including bedrock composition, infiltration capacity, surface runoff, and more. Furthermore, studies in conjunction with high-resolution satellite data in different geological and climatic settings help in understanding the current state of landforms and their associated processes, as well as soil characteristics, soil erosion, drainage management, and the assessment of groundwater potential conditions for effective watershed

planning and management (Vijith, 2006; Rekha et al., 2011; Gajbhiye, 2015; Pakhmode et al., 2003; Agarwal, 1998).

Researchers consistently emphasise the efficacy of GIS and remote sensing data, such as SRTM-DEM, for undertaking morphometric analysis. These tools are highly regarded for their ability to analyse drainage parameters, landforms, and hydrological characteristics at both the basin and sub-basin levels. They are also known for their reliability, accuracy, and efficiency in estimating morphometric parameters. This makes them valuable for planning and managing watersheds (Magesh et al., 2013; Jitheshlal et al., 2013; Singh et al., 2013; Rai et al., 2017; Pande & Moharir, 2017; Salvi et al., 2017).

Researchers from all around the world study the morphometric analysis of basins in a variety of settings using GIS and remote sensing approaches. This variety of uses reveals the adaptability and value of GIS-based morphometric analysis in numerous landscape contexts. Several studies emphasise the importance of morphometric analysis in understanding hydrological processes and managing river basins (Chandrashekar et al., 2015; Dubey et al., 2015; Kaliraj et al., 2015; Rai et al., 2017; Rautela et al., 2022; Joy et al., 2023). Various studies highlight the significance of morphometric analysis in evaluating the potential of groundwater resources in a basin (Waikar & Nilawar, 2014; Saha et al., 2022). Several works examine the evaluation of flood susceptibility (Wakode et al., 2013; Pophare & Balpande, 2014; Arabameri et al., 2020), as well as the investigation of the impact of sub-basins on main channels (Ogarekpe et al., 2020). On the other hand, some researchers concentrate on examining and comparing reservoir catchments, as well as determining the priority of sub-watersheds through morphometric analysis (Chandrashekar et al., 2015; Choudhari et al., 2018; Odiji et al., 2021).

Given the usefulness of GIS and remote sensing in morphometric analysis, the present study aims to examine the Mahananda River Basin before and after its channel avulsion in the 1970s. The study has two main objectives: first, to illustrate how the river abandoned its old channel in the lower reaches, resulting in the formation of two distinct sub-watersheds; and second, to identify which morphometric parameters—linear, areal, relief, and tectonic—show significant variation when comparing the original basin with the two sub-watersheds formed after the avulsion.

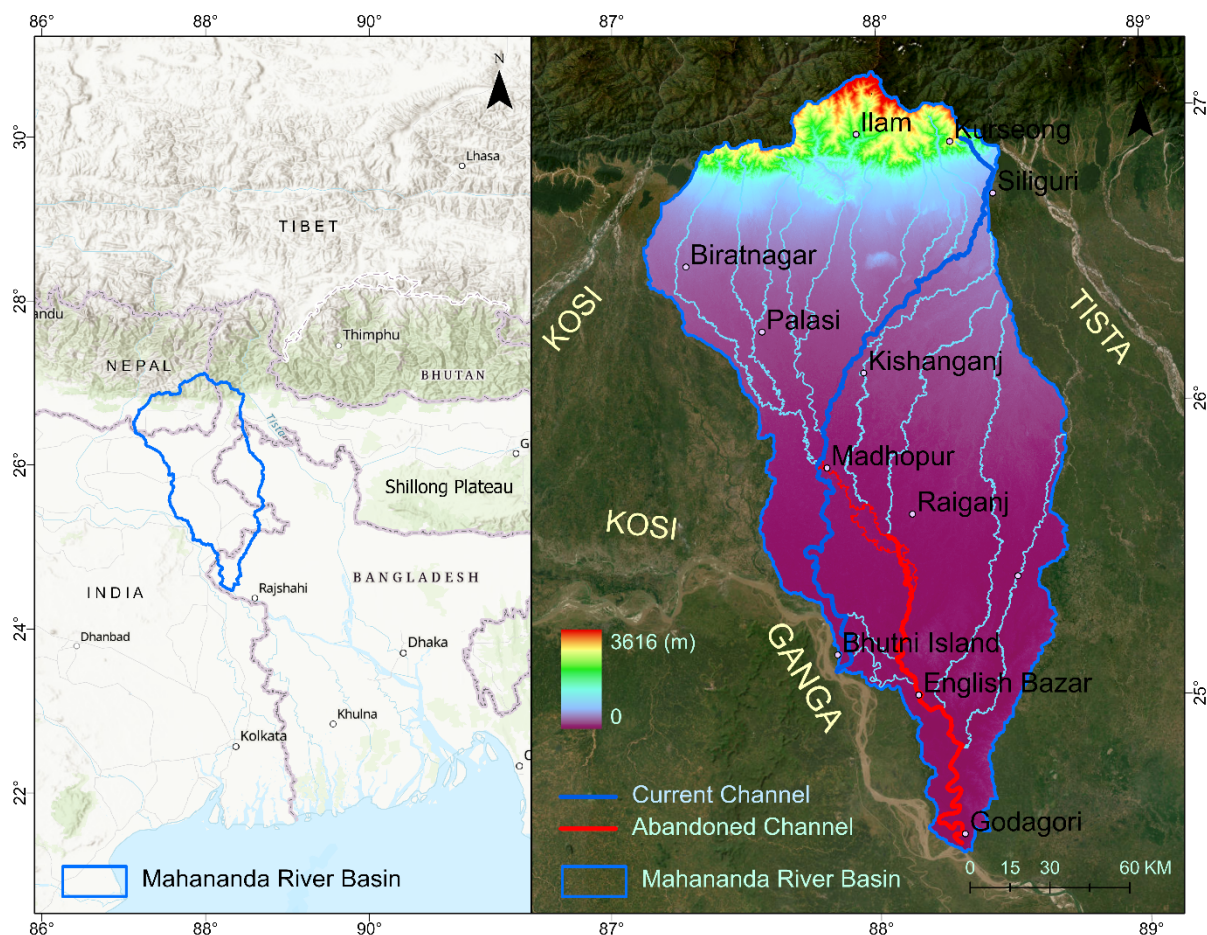
METHODS

Study Area

The Mahananda River originates in the Darjeeling Himalayan hills, specifically within the Kurseong subdivision of Darjeeling District, West Bengal, India, which forms part of the Eastern Himalaya. It is formed by the convergence of three streams descending from the Mahaldiram Range (Siwalik Himalaya): Mahal Diram Forest (26°55'0.55"N, 88°19'47.15"E), Latpanechar Forest (26°53'27.3"N, 88°22'52.3"E), and Paglajhora Falls near Shibkhola Tea Garden (26°52'47.2"N, 88°18'12.3"E) (Sarkar

et al., 2022). These streams converge near Sittong village ($26^{\circ}52'13.20''\text{N}$, $88^{\circ}21'13.20''\text{E}$), and the river continues its course from Shivkhola ($26^{\circ}51'48''\text{N}$, $88^{\circ}21'48''\text{E}$).

Figure 1. Location Map of Mahananda River Basin



The Mahananda is a hill-fed river, with its basin bounded by the Kosi Megafan to the west and the Tista Megafan to the east. Morphologically, the basin may be divided into two major zones: the northern hilly region and the southern alluvial plains. As a transboundary river, it flows through the Indian states of West Bengal and Bihar and forms a 19.91 km natural boundary between India and Bangladesh, from the Fulbari Barrage ($26^{\circ}38'41.94''\text{N}$, $88^{\circ}24'3.20''\text{E}$) to the Mahananda Cross Drainage Bridge near Haptia ($26^{\circ}29'48.00''\text{N}$, $88^{\circ}19'4.85''\text{E}$). The entire basin spans across India, Bangladesh, and Nepal (Figure 1).

The drainage system of the Mahananda River Basin includes numerous tributaries, which differ between the current and abandoned channels. The current Mahananda Basin receives inflow from significant right-bank tributaries such as the Balasan, Mechi, and Kankai rivers, while its left-bank tributaries are relatively minor. Conversely, the abandoned Mahananda Basin was historically fed by prominent left-bank tributaries like the Tangon, Punarbhaba, and Nagar rivers, along with the right-bank Kalindri River. These tributaries have played a critical role in shaping the distinct hydrological regimes of their respective basins (Table 1).

Geologically and geomorphologically, the Mahananda River Basin presents a highly diverse landscape. It flows through a structural depression between the Rajmahal and Garo Hills, forming part of the Bengal Basin. The upper basin is characterized by Quaternary deposits, including metamorphic and sedimentary rocks such as Darjeeling Gneiss, schist, sandstone, and quartzite, while the lower basin is dominated by alluvial deposits consisting of silt, sand, and clay. The basin is further divided into six geomorphic units: Himalayan Mountain, Himalayan Foothills, Himalayan Foredeep, Dinajpur Slope, Rangpur Saddle, and Bogra Slope. These geological characteristics contribute to complex fluvial dynamics and make the basin highly susceptible to avulsion (Sarkar, 2024).

Field investigations conducted between 2018 and 2023 indicate that the average discharge in the lower reaches of the Mahananda River ranges from 50.32 to 1,418.25 cubic metres per second. Rainfall in the basin varies considerably, ranging from 3,753.09 mm in the upper basin to 1,453 mm in the lower reaches (2007–2023), according to data from the Irrigation and Waterways Department, Siliguri Division, and the District Disaster Management Plan, Malda. According to Wadia (1975), the upper Mahananda Basin is composed primarily of Quaternary deposits, while the lower basin consists of recent alluvial formations.

Table 1. Major Tributaries of the Current and Abandoned Mahananda River Basins, Including Their Hierarchy and Lengths

Name	Bank	Tributary	Tributary's Tributary	Length (km)
Present Channels				
Current Mahananda River (296.72 km)	Right Bank	Balasan		44.65
		Mora Balasan		53.72
		Chengra		65.61
		Mechi		86.55
			Biring Khola	76.925
		Kankai		151.67
			Ratuwa Khola	94.5803
		Parman		228.29
			Chisang Khola	148.261
	Panar		93.66	
	Ghasla Kamla		170.467	
	Left Bank	Gulma Nadi		12.16
Dauk River			112.10	
Abandoned Channels				
Abandoned Mahananda River (258.36 km)	Left Bank	Sudhani		150.31
		Nagar		181.14
			Kulik	138.21
		Tangon		258.96
	Punarbhaba		198.22	
	Right Bank	Kalindri		65.91

Source: Derived and calculated by the authors using Survey of India topographical sheets, Google Earth Pro, and satellite imagery (Landsat), through GIS-based analysis

Data Sources

The present study relied primarily on Digital Elevation Models (DEMs) and historical maps to delineate watersheds and extract stream networks with greater precision. Two DEMs, differing in spatial resolution, were employed to enable a comparative assessment of terrain characteristics. DEM resolution plays a crucial role in terrain-derived indices, especially slope-based morphometric parameters, as demonstrated in comparative modeling studies (Moody & Hickey, 2025).

- The 30-meter Shuttle Radar Topographic Mission (SRTM) DEM, obtained from the USGS Earth Explorer (<https://earthexplorer.usgs.gov/>), and
- The 12.5-meter ALOS PALSAR DEM, sourced from the Alaska Satellite Facility (<https://asf.alaska.edu/datasets/daac/alos-palsar/>).

Using both datasets facilitated a more nuanced interpretation of the landscape at varying spatial scales. While the SRTM DEM, widely recognized in global hydrological studies and foundational to datasets like HydroSHEDS, offered a consistent base, the finer resolution of the ALOS PALSAR DEM proved particularly valuable in detecting subtle drainage divides and minor tributaries within low-relief floodplain areas. To ensure accuracy, the stream network derived from these DEMs was cross-verified using Google Earth Pro imagery and Survey of India (SoI) topographic sheets, following which the final stream network was selected for detailed analysis.

In addition, historical Survey of India (SoI) toposheets from 1917, 1928, and 1974 (at scales ranging from 1:1,000,000 to 1:50,000), along with Landsat satellite imagery (Landsat 2 MSS from 1975, Landsat 8 and 9 OLI from 2022), were used to detect historical and recent channel positions and to validate the extracted stream features (Table 2).

Table 2. Details of the Maps and Satellite Imagery Used in the Study

SL	Source	Number	Scale/resolution	Year(s)
1	SoI, Colonel Sir S. G. Burrard, K.C.S.I, R.E., F.R.S., Survey General of India	72, 78	1:1,000,000	1917
2	SoI, Brigadier E. A. Tandy R.E., Survey General of India	72 O, 72 P, 78 C, 78D	1:253,440	1928
3	SoI, Dr. Hari Narain, Survey General of India	72 O/11, 72 O/12, 72 O/13, 72 O/14, 72 O/15, 72 O/16, 78 C/2, 78 C/3, 78 C/4, 78 C/7	1:50,000	1974
4	Landsat 2 MSS images	Path 149, Row 042, 043	30 m	24 th Dec. 1975
5	Landsat 8 OLI images	Path 149, Row 041, 042, 043	30 m	24 th Dec. 2022
6	Landsat 9 OLI images	Path 149, Row 042	30 m	07 th Dec. 2022
7	SRTM DEM	N24 E87, N24 E88, N25 E87, N25 E88, N26 E87, N26 E88	30 m	23 rd Sep. 2014

Watershed and Stream Network Delineation

Based on a comparative analysis of the aforementioned datasets, it was inferred that the channel avulsion of the Mahananda River occurred prior to the 1970s. To delineate the pre-avulsion basin, georeferenced Survey of India (SoI) topographic sheets from the years 1928 and 1974 were digitized and examined in detail. The post-avulsion basin—comprising the Current Mahananda and Abandoned Mahananda sub-watersheds—was delineated using hydrological analysis tools available in ArcGIS Pro (version 3.2.0), utilizing both the SRTM and ALOS PALSAR DEMs.

Standard hydrological preprocessing steps such as sink filling, flow direction and accumulation, stream definition, and watershed delineation were executed within ArcGIS Pro. The resulting stream networks and watershed boundaries were further refined through comparison with HydroSHEDS-derived stream data, which is also based on the SRTM DEM. Final delineations were adjusted based on congruence between outputs from both DEMs and validated through visual interpretation using high-resolution imagery from Google Earth Pro.

In addition, major tributaries derived from DEM analyses were cross-verified against multiple sources, including SoI maps, Landsat satellite imagery, and Google Earth Pro, ensuring spatial accuracy in drainage delineation. This multi-source validation approach significantly enhanced the reliability of basin boundaries and stream networks for both the current and abandoned Mahananda systems. All spatial datasets were consistently projected to WGS 1984 UTM Zone 45N to maintain uniformity throughout the analysis.

Morphometric Analysis

A comprehensive comparative morphometric assessment was undertaken to evaluate how the Mahananda basin responded to channel avulsion. Based on an extensive literature review, 53 morphometric parameters were selected—covering linear, areal, relief, and tectonic aspects. Morphometric calculations were performed using established mathematical formulas (Table 3). The parameters were derived from GIS-based spatial analysis and categorized as follows:

a) Linear Aspects: Parameters such as stream order (So), stream length (Lu), stream length ratio (Rl), and bifurcation ratio (Rb) were computed using Strahler's and Horton's hierarchical models. The sinuosity index (Snt) was employed to assess river channel patterns, distinguishing between straight and meandering segments.

b) Areal Aspects: Areal parameters—including drainage density (Dd), stream frequency (Fs), form factor (Rf), and elongation ratio (Re)—were calculated to evaluate watershed shape, drainage efficiency, and runoff behavior. Lower form factor and elongation ratio values were indicative of elongated basins, which typically respond slowly to peak discharge events.

c) Relief Aspects: Topographic parameters such as basin relief (Bh), relative relief (Rr), ruggedness number (Rn), and gradient ratio (Rg) provided insight into elevational variability and erosional dynamics. These metrics helped assess sediment transport potential and landscape maturity.

d) Tectonic Aspects: To detect tectonic influence, three indices were analysed:

- Transverse Topographic Symmetry Factor (TTSF) – used to identify lateral tilting (Figure 2).
- Asymmetry Factor (AF) – used to assess directional tilt of the basin relative to its main stream (Figure 2).
- Hypsometric Integral (HI) – used to estimate erosion stage, with values nearing 1 indicating youthful terrain, and values near 0 representing mature or eroded landscapes.

These parameters allowed for a holistic geomorphic and tectonic assessment of how channel avulsion has influenced watershed evolution in the Mahananda Basin across Nepal, India, and Bangladesh (Figure 3).

Figure 2. Transverse Topography Symmetry Factor (TTSF) (Left) and Asymmetry Factor (AF) of Mahananda River Basins (Right)

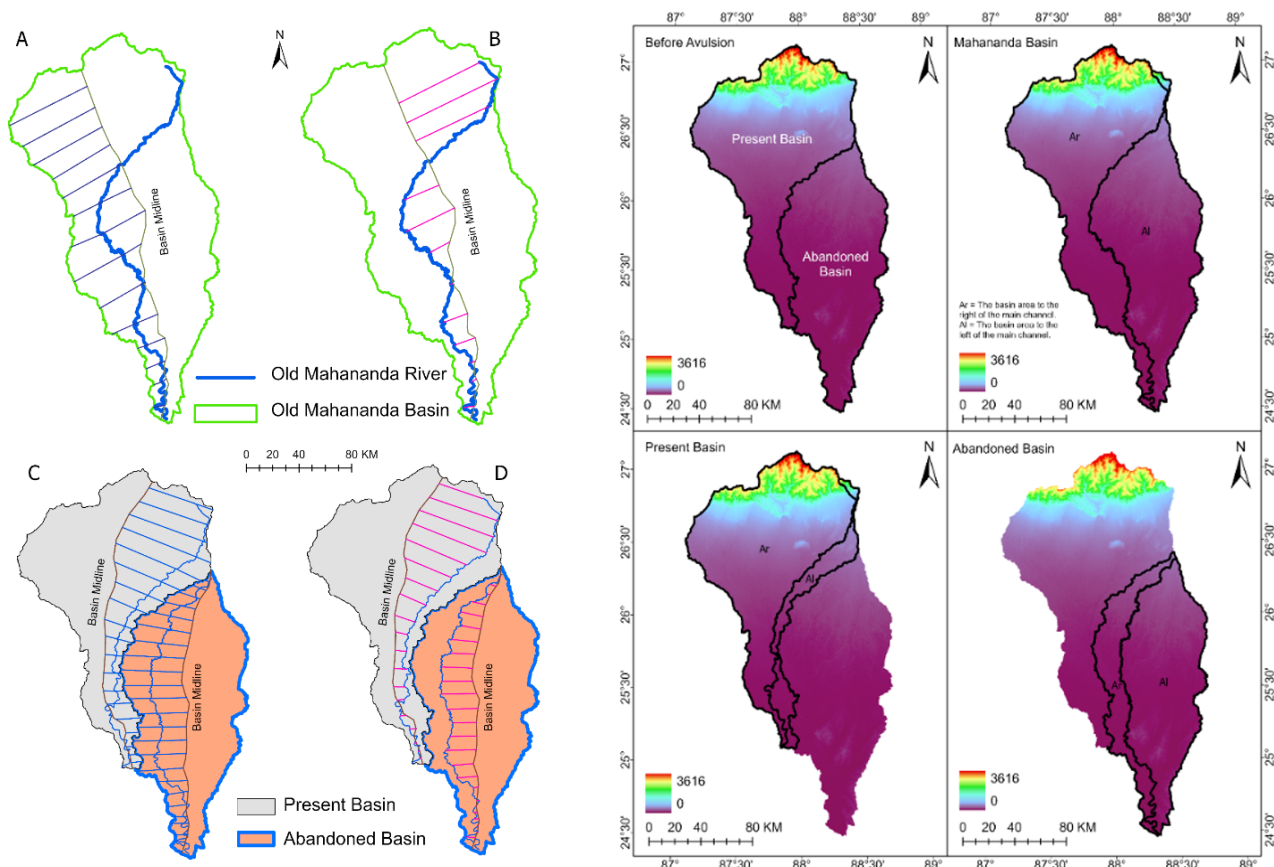


Figure 3. Flowchart of Methodology Used For Comparative Morphometric Analysis Among Mahananda Basins

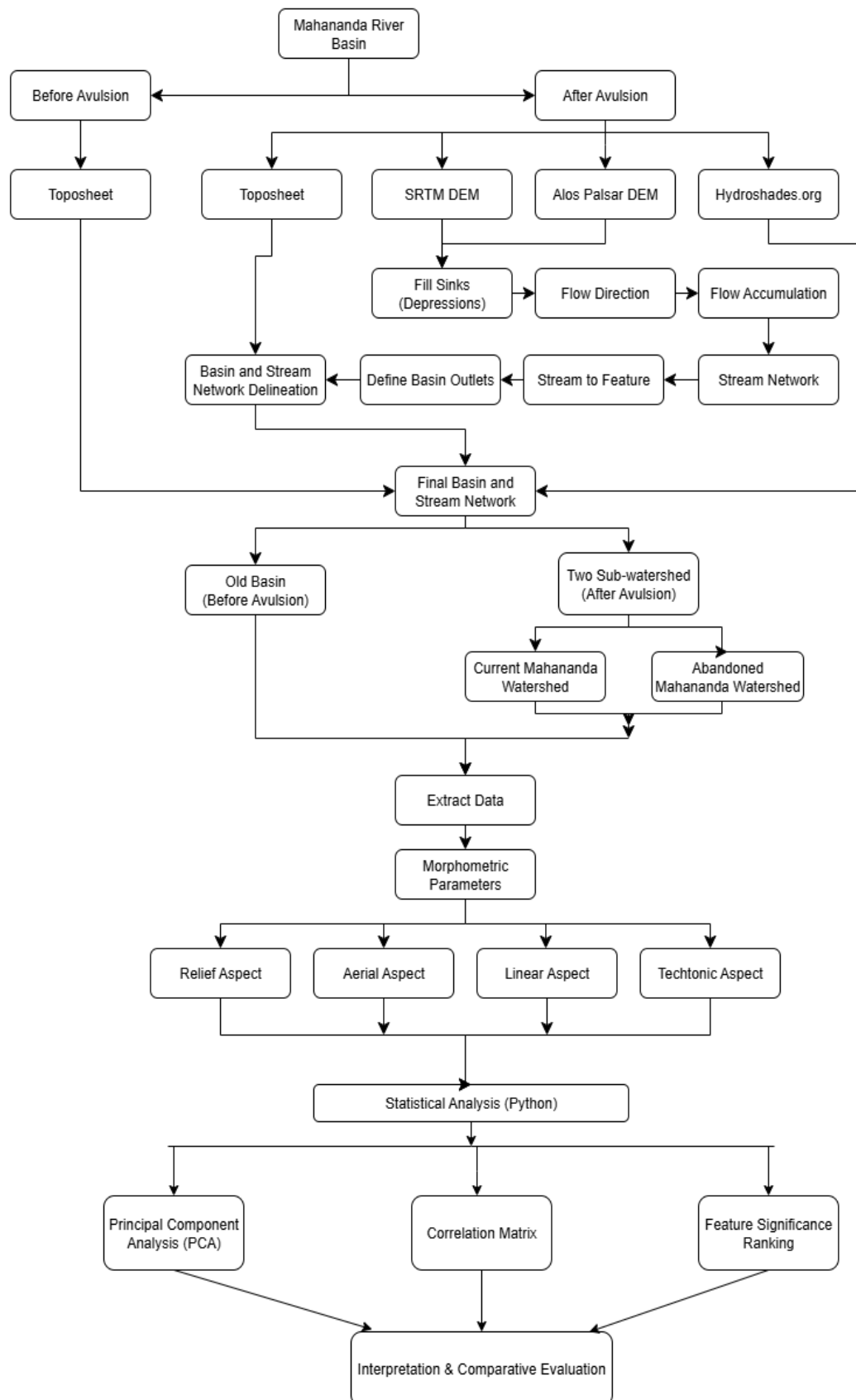


Table 3. Linear, Relief, Areal and Tectonic Aspects of Morphometric Parameters Used for Mahananda River Basins

SL No	Morphometric Parameters	Formula/Definition/ Method	Reference
Linear Aspects			
1	Stream Order (S_o)	Hierarchical order (GIS analysis)	Strahler (1964)
2	Stream Length (L_u)	Length of the streams (GIS analysis)	Horton (1945)
3	Mean Stream Length (L_{sm}) km	$L_{sm} = L_u * N_u^{***}$	Horton (1945)
4	Stream Length Ratio (R_l)	$R_l = L_u / L_u - I$,	Horton (1945)
5	Bifurcation ratio (R_b)	$R_b = N_u / N_u + I$,	Schumm (1956)
6	Mean Bifurcation ratio (R_{bm})	R_{bm} = mean of bifurcation ratio of all orders	Schumm (1956)
7	Rho Coefficient (C_{rh})	$C_{rh} = R_l / R_b$	Horton (1945)
8	Length of main channel (L_c) km	GIS analysis	-
9	Sinuosity Index (S_{nt})	S_{nt} = Actual L_u / Channel Distance	Stolum (1996)
Aerial Aspects			
10	Drainage basin area (A) Km^2	GIS analysis	-
11	Drainage basin perimeter(P) km	GIS analysis	-
12	Length Area Relation (L_{ar})	$L_{ar} = 1.4 * A^{0.6}$	Hack (1957)
13	Leminiscate's (K)	$K = L^2 / A$	Chorley et al. (1957)
14	Stream Frequency (F_s)	$F_s = N^{**} / A$	Horton (1945)
15	Drainage density (D_d) km/km ²	$D_d = L / A$,	Horton (1945)
16	Drainage Intensity (D_i)	$D_i = F_s / D_d$	Smith (1950)
17	Infiltration ratio /number (I_p)	$I_f = F_s * D_d$	Faniran (1968)
18	Texture Ratio(T)	$T = N / P$	Horton (1945)
19	Form Factor (R_f)	$R_f = A / L^2$	Horton (1932)
20	Circulatory Ratio (R_c)	$R_c = 4\pi A / P^2$	Miller (1953)
21	Elongation Ratio (R_e)	$R_e = 2\sqrt{(A/\pi)} / L_b$	Schumm (1956)
22	Relative Perimeter (P_r)	$P_r = A / P$	Schumm (1956)
23	Basin Length (L_b) km	GIS analysis	Schumm (1956)
24	Mean Basin Width (W_b) km	$W_b = A / L_b$	Horton (1932)
25	Compactness Co-efficient (C_c)	$C_c = 0.2821 * P / A^{0.5}$	Gravelius (1914)
26	Shape Index (S_w)	$S_w = I / F_s$	Horton (1932)
27	Shape factor (S_f)	$S_f = L_b^2 / A$	Horton (1932)
28	Length of overland flow (L_{of}) km	$L_{of} = I / 2D_d$	Horton (1945)
29	Fitness ratio (R_f)	$R_f = L_c / P$	Melton (1957)
30	Wandering ratio (R_w)	$R_w = L_c / L_b$	Smart & Surkan (1967)
31	Constant of channel maintenance(C)	$C = I / D_d$	Horton (1945)

SL No	Morphometric Parameters	Formula/Definition/ Method	Reference
Relief aspects			
32	Maximum elevation (M_a) m	GIS analysis	-
33	Minimum elevation (M_i)m	GIS analysis	-
34	Basin Relief (B_h)	$M_a - M_i$	Schumm (1956)
35	Relative relief (R_r)	B_h/P	Horton (1945)
36	Relief Ratio (R_h)	$R_h = B_h/L_b$	Schumm (1956)
37	Ruggedness Number (R_n)	$R_n = B_h * D_d$	Strahler (1958)
38	Ruggedness Index (R_i)	$R_i = D_d * (R_r/1000)$	Schumm (1956)
39	Melton's Ruggedness Number (M_{rn})	$(M_a - M_i)/A^{0.5}$	Melton (1965)
40	Watershed/ basin Slope (S_b)	$S_b = H/L_b$	Miller (1953)
41	Elevation at Source (E_s)	GIS analysis	
42	Elevation at Mouth (E_m)	GIS analysis	
43	Gradient Ratio (R_g)	$R_g = (E_s - E_m)/L_b$	Sreedevi et al. (2005)
44	Total Basin relief(H) m	$H = M_a - E_m$	Strahler (1952)
45	Total Contour length (C_{tl}) km	GIS analysis	-
46	Contour Interval (C_i) m	GIS analysis	-
47	Average slope (S)%	$S = (M_a * (C_{tl}/H)/(10 * A)$	Wentworth (1930)
48	Mean slope of the basin (S_m) %	$S_m = (C_{tl} * C_i)/A$	Chorley (1969)
49	Coarse Ratio (C_r)	$C_r = B_h * D_d$	Chorley (1966)
50	Dissection Index (D_i)	$DI = R_r/A_r$ Where, R_r =Relative Relief; A_r =Absolute Relief	Dov Nir (1957)
Tectonic Aspects			
51	Transverse Topographic Symmetry Factor (TTSF)	$T = Da/Dd$	Cox (1994)
52	Asymmetry factor (AF)	$AF = (AreaRight/AreaTotal) \times 100$	Keller and Pinter (1996)
53	Hypsometric Integral (HI)	$HI = (h/H)/(a/A)$, Where, h = absolute relief, H = highest relief in the area; a = area of absolute relief (h) A = Total basin area.	A.N. Strahler (1952)

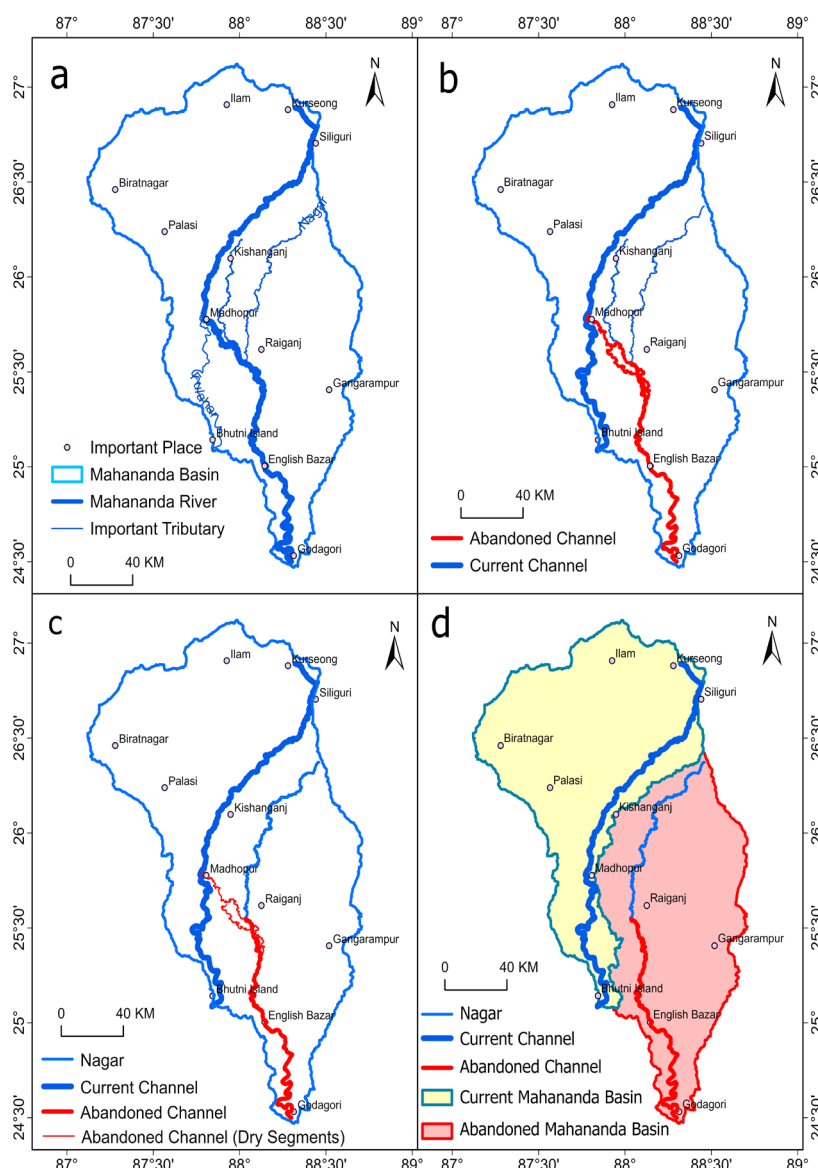
RESULTS

Channel Avulsion and Morphological Realignment of the Mahananda River

Historically, prior to its channel avulsion, the Mahananda River flowed through the districts of Darjeeling and Uttar Dinajpur in West Bengal, as well as the districts of Kishanganj, Purnia, and Katihar in Bihar, before entering the Malda district in West Bengal. The Malda district is geographically divided into two distinct regions by the river: the eastern part, characterised mainly by older, less fertile alluvial soil known as *Barind*, and the western part, which is subdivided by the Kalindri River into a northern area called *Tal*, prone to flooding during the rainy season, and a southern area, *Diara*, known for its fertile land and dense population.

The Mahananda once met the Ganges (Padma in Bangladesh) at Godagiri in the Nawabganj district of Bangladesh ($24^{\circ}30'1.05''$ N, $88^{\circ}17'56.83''$ E). Following the channel avulsion, the Mahananda now joins the Ganges at Bhutni Island in the Malda district of West Bengal, India ($25^{\circ}5'1.82''$ N, $87^{\circ}50'13.10''$ E). This geographical shift has caused the river's length to decrease from 444.40 km to 296.72 km. The river abandoned its former course near Marua village in the Baisi subdivision of Purnia district, Bihar, India ($25^{\circ}47'7.73''$ N, $87^{\circ}47'6.96''$ E), between 1928 and 1970, resulting in the formation of two sub-watersheds: the Current Mahananda Watershed (CMW) and the Abandoned Mahananda Watershed (AMW) (Figure 4–5). These are distributed across several geographical regions, as shown in Table 4. Information pertaining to the tributaries of the current and defunct channels is provided in Table 1.

Figure 4. Spatio-Temporal Evolution of the Mahananda River Channel and Watershed Formation



(a) Pre-avulsion channel path (1917–1974, Sol toposheets); (b) Abandoned channel as seen in 1975 Landsat; (c) Present-day and abandoned channels; (d) Formation of Current and Abandoned Mahananda Basins)

Table 4. Spatial and Administrative Distribution of the Mahananda River Basin Before and After Avulsion Across Nepal, India, and Bangladesh

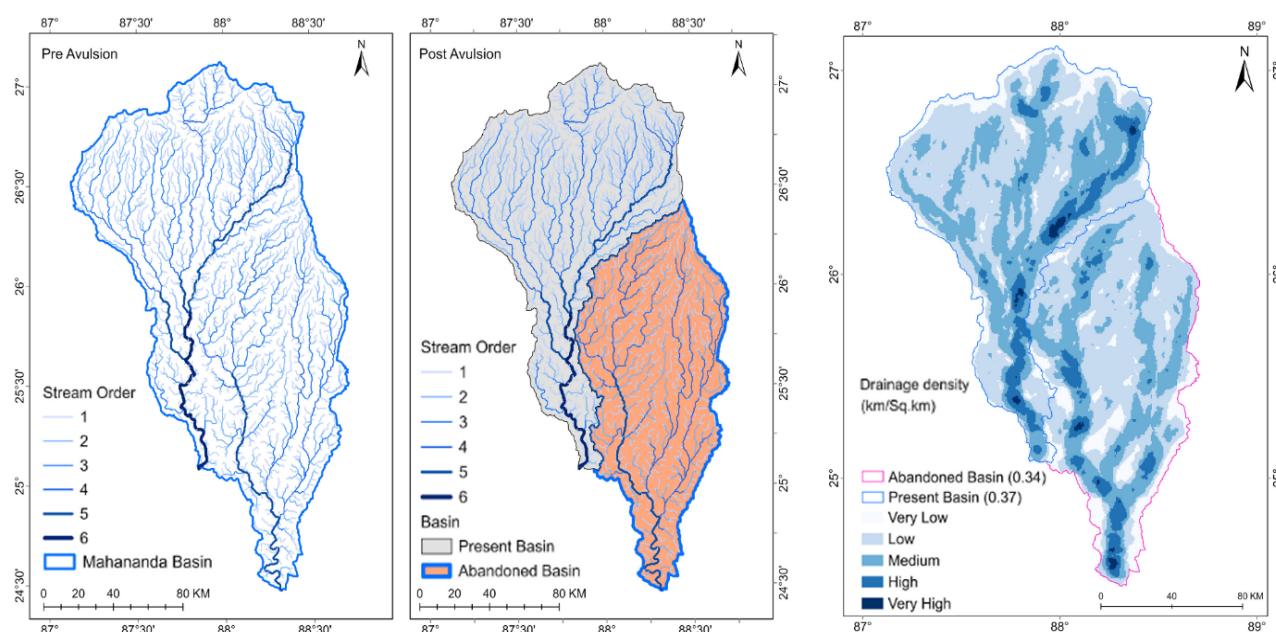
Mahananda River Basin (before Avulsion)						
Country	State/Division	District/Zila/Anchal	Area (Sq. km.)		Area %	
Bangladesh	Rajshahi	Naogaon	352.75	4932.74	1.41	19.68
Bangladesh	Rajshahi	Nawabganj	1059.45	4.23		
Bangladesh	Rajshahi	Rajshahi	71.41			
Bangladesh	Rangpur	Dinajpur	1288.72	0.28		
Bangladesh	Rangpur	Panchagarh	380.84	5.14		
Bangladesh	Rangpur	Thakurgaon	1779.57	1.52		
				7.10		
Nepal	East	Koshi	2276.33	5580.80	9.08	22.26
Nepal	East	Mechi	3304.47	13.18		
India	Bihar	Araria	1297.03	14557.20	5.17	58.06
India	Bihar	Katihar	1681.08	6.71		
India	Bihar	Kishanganj	1933.15	7.71		
India	Bihar	Purnia	959.41			
India	West Bengal	Dakshin Dinajpur	1218.36	3.83		
India	West Bengal	Darjiling	1308.27	4.86		
India	West Bengal	Jalpaiguri	43.83	5.22		
India	West Bengal	Maldah	2802.89			
India	West Bengal	Uttar Dinajpur	3313.17	0.17		
				11.18		
				13.22		
Total			25070.74	25070.74	100.00	100.00
Current Mahananda River Watershed (After Avulsion)						
Bangladesh	Rangpur	Panchagarh	123.49	123.49	0.92	0.92
Nepal	East	Koshi	2276.33	5580.80	16.92	41.48
Nepal	East	Mechi	3304.47	24.56		
India	Bihar	Araria	1297.03	7749.18	9.64	57.60
India	Bihar	Katihar	1147.87	8.53		
India	Bihar	Kishanganj	1921.68	14.28		
India	Bihar	Purnia	959.40			
India	West Bengal	Darjiling	1308.27	7.13		
India	West Bengal	Jalpaiguri	43.83	9.72		
India	West Bengal	Maldah	573.34			
India	West Bengal	Uttar Dinajpur	497.76	0.33		
				4.26		
				3.70		
Total			13453.47	13453.47	100.00	100.00

Abandoned Mahananda River Watershed (After Avulsion)

Country	State/Division	District/Zila/Anchal	Area (Sq. km.)		Area %	
Bangladesh	Rajshahi	Naogaon	352.75	4809.25	3.04	41.40
Bangladesh	Rajshahi	Nawabganj	1059.45	9.12		
Bangladesh	Rajshahi	Rajshahi	71.41	0.61		
Bangladesh	Rangpur	Dinajpur	1288.72	11.09		
Bangladesh	Rangpur	Panchagarh	257.35	2.22		
Bangladesh	Rangpur	Thakurgaon	1779.57	15.32		
India	Bihar	Katihar	533.21	6808.02	4.59	58.60
India	Bihar	Kishanganj	11.47	0.10		
India	Bihar	Purnia	0.01	0.00		
India	West Bengal	Dakshin Dinajpur	1218.36	10.49		
India	West Bengal	Maldah	2229.56	19.19		
India	West Bengal	Uttar Dinajpur	2815.41	24.23		
Total			11617.27	11617.27	100.00	100.00

Source: Derived and calculated by the authors based on Survey of India topographical sheets, Google Earth Pro, and satellite imagery (Landsat), using GIS-based analysis

Figure 5. Comparison of Stream Order (Left) and Drainage Density (Right) in the Mahananda Watersheds Before and After Channel Avulsion



Morphometric Variability and Watershed Comparison

The morphometric comparison among the Original Mahananda Basin (OMB), Current Mahananda Watershed (CMW), and Abandoned Mahananda Watershed (AMW) reveals marked differences resulting from channel avulsion. Table 5 presents quantitative values for 53 morphometric parameters across the three basins, including percentage changes relative to the original basin. These variations are visually represented in Figure 6, highlighting the magnitude and direction of change in each parameter.

Key Morphometric Shifts – Linear Aspects

Significant reductions were observed in stream length (Lu), basin length (Lb), and main channel length (Lc) in both CMW and AMW, with AMW showing a more severe decrease (e.g., Lu: -55.4%). The bifurcation ratio (Rb) increased in AMW (+23.6%), suggesting reduced tributary branching and possible structural control. The sinuosity index (Snt) rose in AMW, indicating a transition toward more winding but disconnected channels. These changes reflect the fragmentation of the drainage network post-avulsion, especially in the abandoned basin.

Key Morphometric Shifts – Areal Aspects

Parameters such as drainage density (Dd) and stream frequency (Fs) remained relatively stable in CMW but declined in AMW, reflecting a weakening of surface hydrological connectivity. Form factor (Rf) and elongation ratio (Re) decreased across both sub-watersheds, indicating a more elongated basin form, which typically results in a delayed runoff response. AMW showed stronger reductions in compactness (Cc) and mean basin width (Wb), suggesting the contraction of the active drainage area.

Key Morphometric Shifts – Relief Aspects

Topographic contrasts were among the most striking outcomes. Basin relief (Bh) declined by more than 97% in AMW, compared to 51% in CMW. Other indicators, such as ruggedness number (Rn), Melton's number (Mrn), and gradient ratio (Rg), similarly dropped, highlighting the flattening and geomorphic stagnation of the abandoned basin. These values point to diminished erosional power and sediment transport capacity following disconnection from the main channel.

Key Morphometric Shifts – Tectonic Aspects

Tectonic control over basin geometry and flow alignment was assessed using the Transverse Topographic Symmetry Factor (TTSF), Asymmetry Factor (AF), and Hypsometric Integral (HI). CMW showed a significant increase in AF (+54.5%) and TTSF (+42.5%), indicating lateral tilting likely linked to structural deformation. AMW, despite its disconnection, still exhibits mild asymmetry and a slightly higher HI value (0.50), suggesting a preserved erosional stage in upper terrain zones.

Table 5. Comparative Morphometric Parameters Across Old Mahananda Basins (OMB), Current (CMW), and Abandoned (AMW) Mahananda Watersheds With Percentage Variation

Parameters	OMB	CMW	AMW	% Change CMW	% Change AMW
A	25070.80	13453.50	11617.30	-46.34	-53.66
P	898.84	743.66	640.70	-17.26	-28.72
Pr	27.89	18.09	18.13	-35.14	-34.99
Lb	280.85	209.15	199.35	-25.53	-29.02
Lar	610.42	420.17	384.76	-31.17	-36.97
Wb	89.27	64.33	58.28	-27.94	-34.72
K	3.15	3.25	3.42	3.34	8.74
Cc	1.60	1.81	1.68	12.99	4.75
Lc	444.51	296.72	372.15	-33.25	-16.28
Lu	8851.35	4902.46	3948.90	-44.61	-55.39
Lsm	5.25	5.47	5.01	4.04	-4.61
Rl	2.20	2.15	3.15	-2.50	42.81
Rb	4.29	3.89	5.30	-9.42	23.56
Rbm	4.29	3.89	5.30	-9.42	23.56
Fs	0.07	0.07	0.07	0.00	1.49
Dd	0.35	0.36	0.34	3.12	-3.68
Di	0.19	0.18	0.20	-3.68	5.26
If	0.02	0.02	0.02	0.00	-4.17
T	1.88	1.21	1.23	-35.68	-34.40
Rf	0.32	0.31	0.29	-3.14	-8.18
Rc	0.39	0.31	0.36	-21.54	-8.72
Re	0.64	0.63	0.61	-1.57	-4.09
Crh	0.51	0.55	0.59	7.80	15.59
Sw	14.88	15.00	14.74	0.80	-0.91
Sf	3.15	3.25	3.42	3.34	8.74
Lof	1.42	1.37	1.47	-3.11	3.88
Fr	0.50	0.40	0.58	-19.39	17.37
Rw	1.58	1.42	1.87	-10.36	17.94
C	2.83	2.74	2.94	-3.11	3.88
Ma	3616.00	1800.00	88.00	-50.22	-97.57
Mi	14.00	23.00	14.00	64.29	0.00
Bh	3602.00	1777.00	74.00	-50.67	-97.95
Rr	4.01	2.39	0.12	-40.35	-97.13
Rh	12.83	8.50	0.37	-33.75	-97.11
Rn	1271.70	647.54	25.15	-49.08	-98.02
Ri	0.00	0.00	0.00	0.00	-100.00
Mrn	22.75	15.32	0.69	-32.66	-96.98
Sb	12.83	8.50	0.37	-33.75	-97.11
Es	328.00	328.00	79.00	0.00	-75.91
Em	14.00	23.00	14.00	64.29	0.00
Rg	1.50	1.46	0.33	-2.99	-78.31
H	3602.00	1777.00	74.00	-50.67	-97.95

Parameters	OMB	CMW	AMW	% Change CMW	% Change AMW
Ctl	211198.01	157476.47	53707.42	-25.44	-74.57
Ci	10.00	10.00	10.00	0.00	0.00
S	0.85	1.19	0.55	40.19	-34.99
Sm	84.24	117.05	46.23	38.95	-45.12
Cr	10202.39	4876.50	217.70	-52.20	-97.87
Snt	1.68	1.44	1.79	-14.18	6.61
Ttsf	0.60	0.86	0.57	42.45	-5.14
AF	54.94	84.88	27.82	54.51	-49.36
DI	0.00	0.00	0.00	18.18	18.18
HI	0.47	0.47	0.50	0.00	6.38

Source: Calculated by the authors from survey of India Topographical sheets and field survey

Multivariate Analysis and Morphometric Clustering

To reduce dimensionality and detect patterns, Principal Component Analysis (PCA) was applied to the 53 morphometric parameters. The PCA biplot (Figure 7) illustrates that stream length (Lu), basin relief (Bh), and drainage density (Dd) were the dominant variables contributing to differentiation among the basins. CMW clustered closely with OMB, while AMW diverged significantly, confirming the impact of hydrological disconnection. Furthermore, hierarchical clustering analysis (Figure 8), based on PCA scores, supports these findings. The dendrogram structure shows AMW as morphometrically the most distinct, with a greater linkage distance from OMB and CMW. This emphasizes that the abandoned basin has undergone a complete shift in fluvial characteristics, affirming its functional isolation post-avulsion.

Figure 6. Percentage Change in Morphometric Parameters in CMW (Current Mahananda Watershed) and AMW (Abandoned Mahananda Watershed) Relative to the OMB (Old Mahananda Basin)

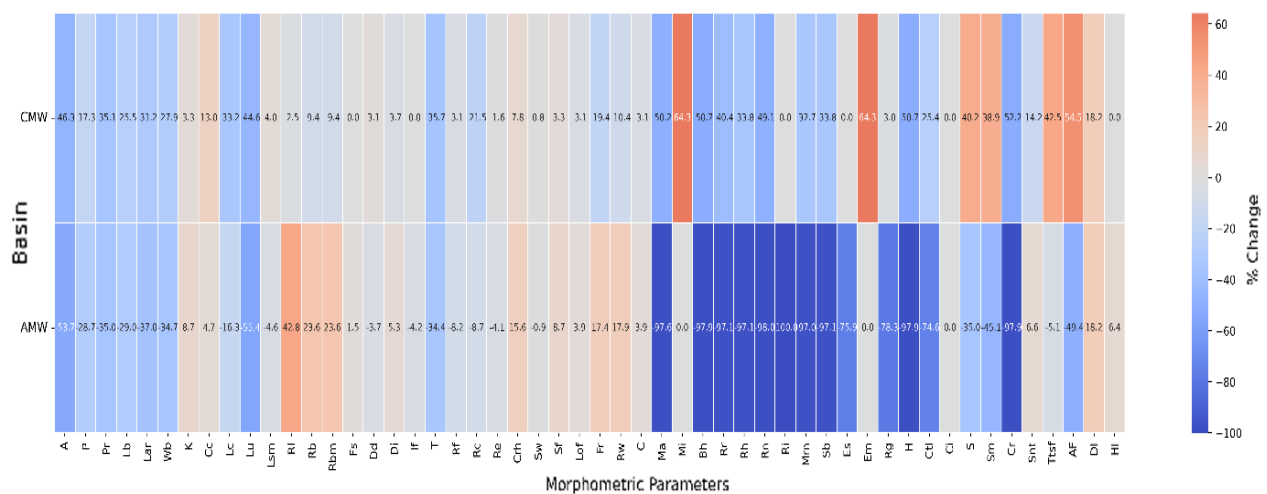
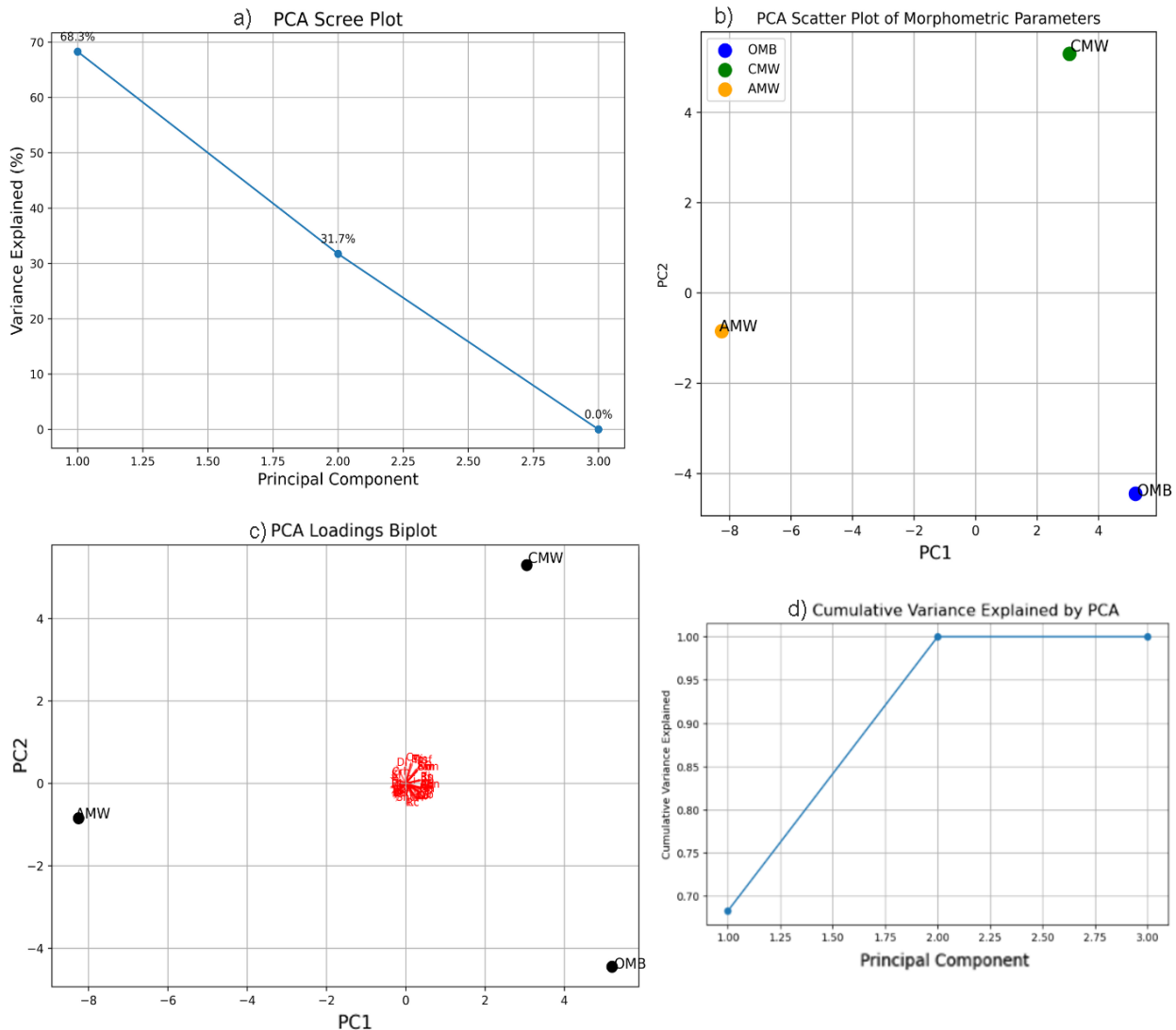


Figure 7. Principal Component Analysis (PCA) of Morphometric Parameters Across the Original (OMB), Current (CMW), and Abandoned (AMW) Mahananda Basins



(a) Scree plot showing variance explained by each principal component; (b) PCA scatter plot displaying spatial clustering of the three basins; (c) PCA loadings biplot highlighting contributing parameters; (d) Cumulative variance explained by the first two components.

Radar and Hypsometric Visualization

The radar chart (Figure 9) provides a comparative view of the morphometric parameters on a logarithmic scale. It clearly shows the relative flattening of AMW's profile compared to OMB and CMW. The hypsometric curve (Figure 9) complements this interpretation by depicting the relative elevation distribution. Both OMB and CMW reflect typical mature-to-youthful erosion stages ($HI \approx 0.47$), whereas AMW's slightly elevated HI (0.50) may suggest that parts of the basin have experienced lesser degradation due to reduced stream activity (Figure 8–10).

Figure 8. Hierarchical Clustering Dendrogram of OMB, CMW, and AMW Based on Morphometric PCA Scores

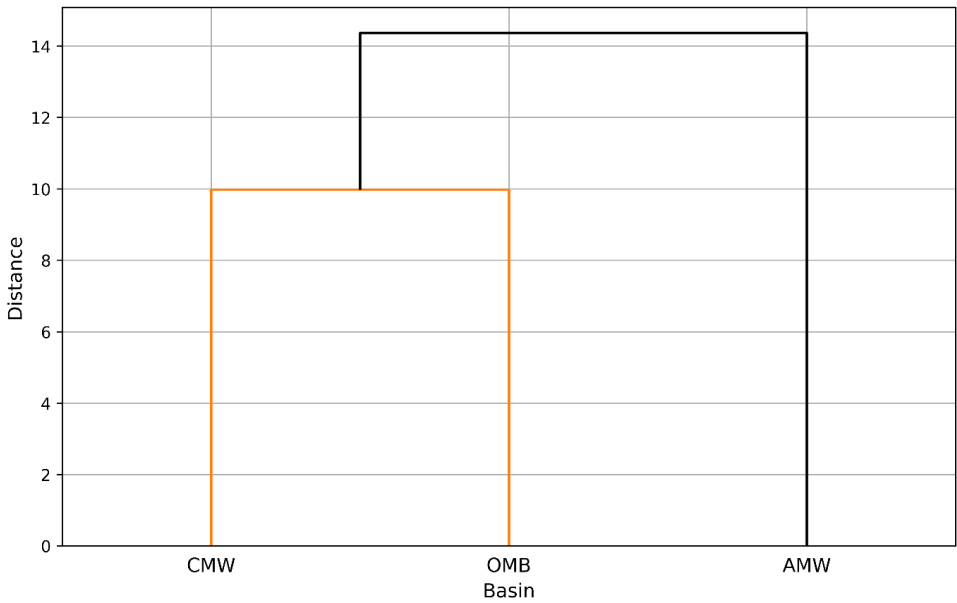


Figure 9. Radar Chart (Log-Scaled) Comparing Morphometric Parameter Profiles Across the Three Watersheds

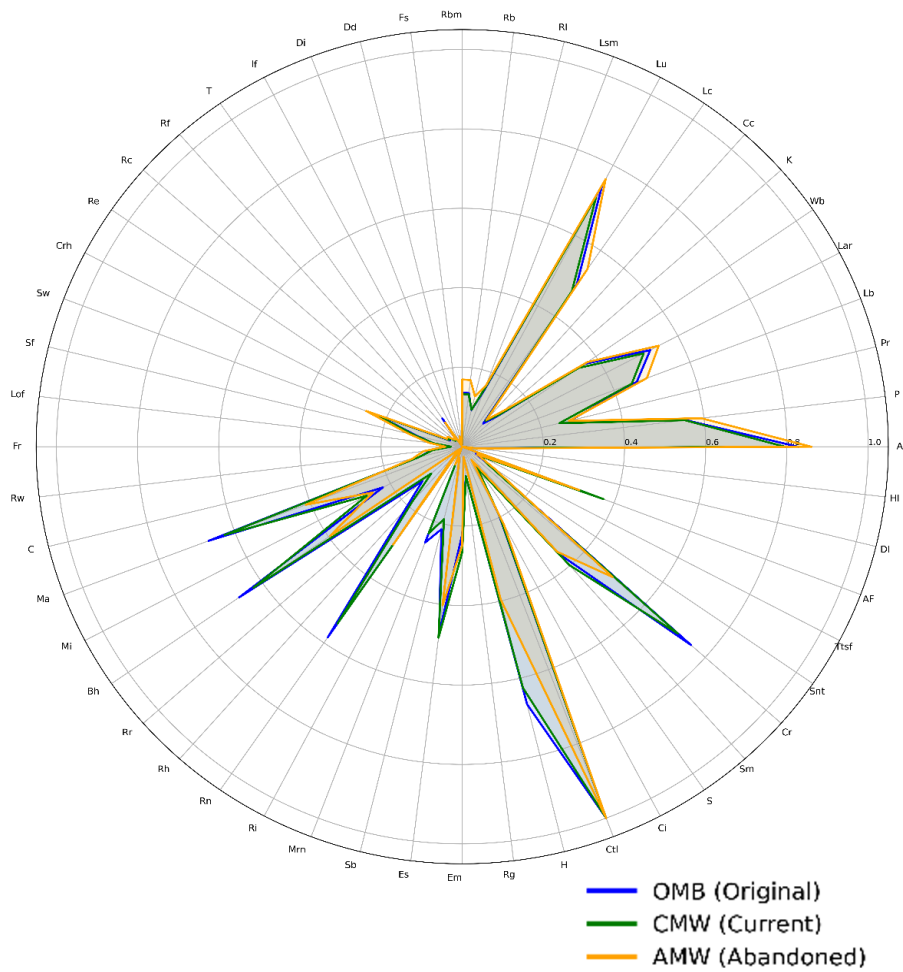
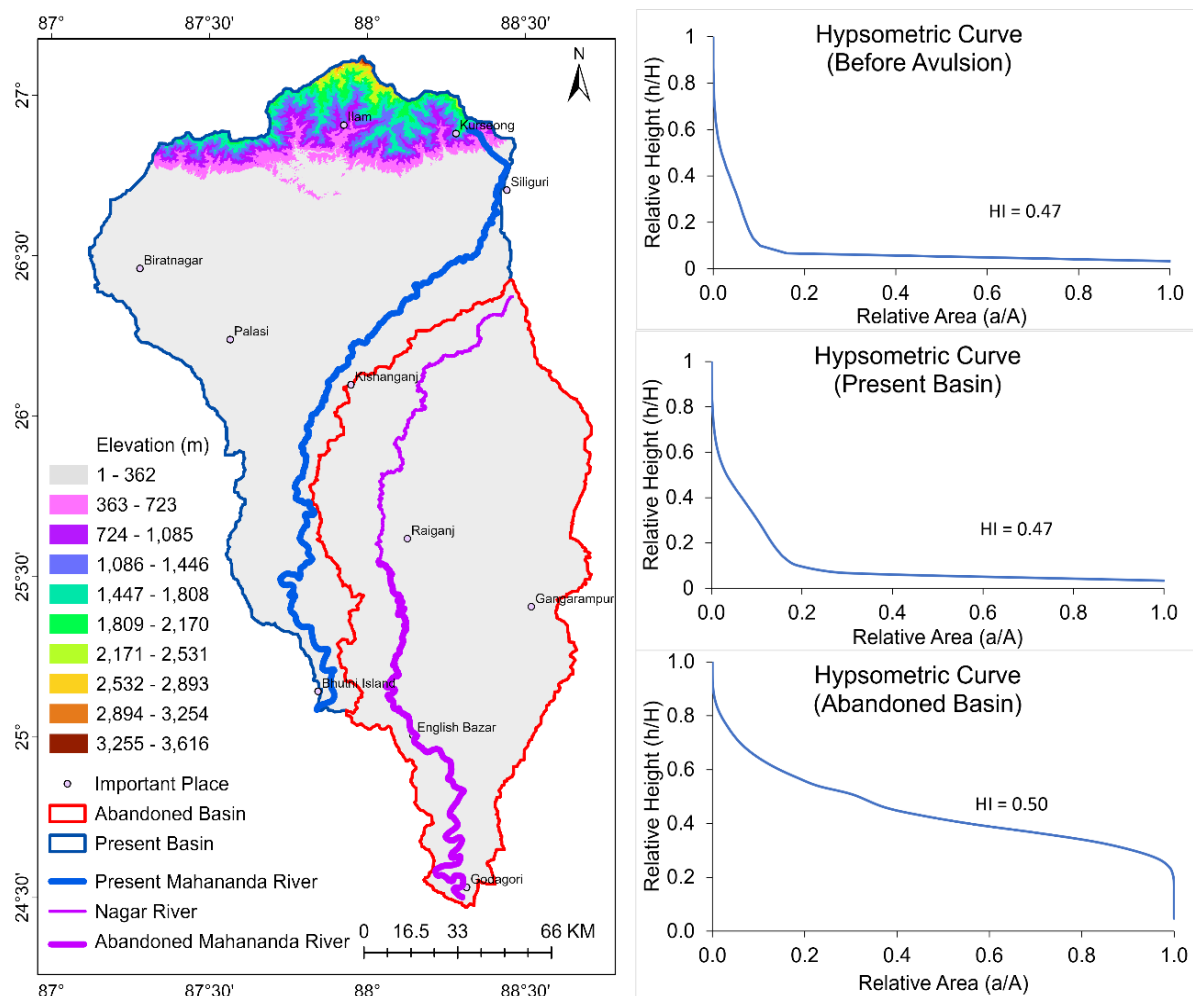


Figure 10. Hypsometric Curves and Integral (Hi) Values for the Mahananda River Watersheds Before and After Avulsion



Summary of Morphometric Insights

The morphometric response to channel avulsion in the Mahananda River Basin is pronounced and multidimensional:

- The Current Mahananda Watershed (CMW), though reduced in extent and relief, retains an active drainage system and exhibits moderate shifts in linear and areal parameters.
- The Abandoned Mahananda Watershed (AMW) exhibits severe reductions in stream length, slope, relief, and dissection indices—signaling its transition toward a geomorphically inactive system.
- Tectonic asymmetry and tilting, evident in both CMW and AMW, suggest that structural controls likely facilitated avulsion and continue to influence drainage evolution.

These findings collectively support the hypothesis that channel avulsion, compounded by tectonic forces, has led to the formation of two morphometrically distinct sub-watersheds within the Mahananda Basin.

Interpretation of Morphometric Shifts and Planning Implications

The morphometric analysis of the Mahananda River Basin before and after channel avulsion reveals distinct structural and functional transformations. The avulsion event, which occurred between 1928 and 1970, not only altered the river's course but also led to the fragmentation of the basin into two morphometrically distinct sub-watersheds: the Current Mahananda Watershed (CMW) and the Abandoned Mahananda Watershed (AMW). The comparative analysis shows significant variations in linear, areal, relief, and tectonic parameters, indicating a strong geomorphological response to the avulsion process. These findings suggest that both natural fluvial dynamics and structural controls have played a role in shaping the present morphology of the basin.

Geomorphic Implications of Channel Avulsion

Channel avulsion has led to significant geomorphic divergence between the sub-watersheds. In the Abandoned Mahananda Watershed (AMW), stream length and relief-related parameters (e.g., Bh, Rn) dropped by over 90%, reflecting a shift toward a low-energy, inactive landscape. Reduced drainage density and stream frequency further suggest diminished surface runoff and channel disconnection. In contrast, the Current Mahananda Watershed (CMW), though reduced in size, retains moderate relief and stream complexity, indicating ongoing fluvial activity. Both post-avulsion basins show more elongated shapes (lower Re, Rf), implying slower runoff and delayed peak discharge response. These patterns confirm that avulsion significantly altered the geomorphic function of the basin—effectively isolating AMW while maintaining hydrological integrity in CMW.

Relief and Tectonic Response

Morphometric indicators in Table 5 highlight how relief and tectonic asymmetry shaped the post-avulsion evolution of the Mahananda Basin. The Abandoned Mahananda Watershed (AMW) shows an extreme decline in basin relief (Bh) and ruggedness number (Rn)—over 97% lower than in the original basin—indicating a flattened, inactive terrain with minimal slope-driven processes. Tectonic influences are evident in elevated values of the Asymmetry Factor (AF) and Transverse Topographic Symmetry Factor (TTSF) in both CMW and AMW, as shown in the PCA biplot (Figure 8). These values suggest structural tilting and lateral displacement, which likely contributed to both the avulsion event and the divergence in morphometric development. Overall, the interaction between tectonic tilting and relief degradation appears central to the watershed transformation, with AMW showing tectonic influence but functional decay, and CMW retaining moderate slope and fluvial activity.

Functional Decay of the Abandoned Watershed

The morphometric signature of the Abandoned Mahananda Watershed (AMW) reflects a clear case of hydro-geomorphic decay. As highlighted in Table 5, AMW has undergone drastic reductions in stream length, drainage density, basin relief, and dissection indices—indicators of a fading fluvial system. Following avulsion, the abandoned channel lost its headwater supply, severing upstream connections.

This led to a breakdown in active erosion, sediment transport, and tributary renewal. The low stream frequency and near-flat hypsometric curve (Figure 7d) further support the interpretation of functional stagnation. Today, AMW functions more as a fossilized basin—structurally present but no longer dynamically engaged in the river system. Its evolution appears to have shifted from fluvial shaping to slow degradation, driven only by residual surface flow and local rainfall.

Parameter Similarity and Dimensional Insights

To better understand interdependencies among morphometric variables, a correlation heatmap (Figure 11) was generated. The results show strong clustering among certain linear, areal, and relief parameters—suggesting redundancy and structural similarity. For example, drainage density (Dd), stream length (Lu), and bifurcation ratio (Rb) exhibit high intercorrelation, especially in the post-avulsion basins. Complementing this, a hierarchical clustering dendrogram (Figure 8), based on PCA scores, highlighted the morphometric divergence of AMW from the original and current basins. This confirms that channel avulsion introduced not just spatial separation, but structural reorganization of morphometric controls. Key parameters that most significantly changed post-avulsion are summarized in Table 6, categorized by morphometric group. The most affected include Lb, Dd, Rb (linear); Cc, A, P (areal); Cr, Rr (relief); and Ctl, AF, HI (tectonic)—pointing to reduced connectivity, shape distortion, and tectonic decoupling of the abandoned basin.

Figure 11. Correlation Heatmap of 53 Morphometric Parameters Across the Three Mahananda Sub-Watersheds, Indicating Variable Interdependence Post-Avulsion

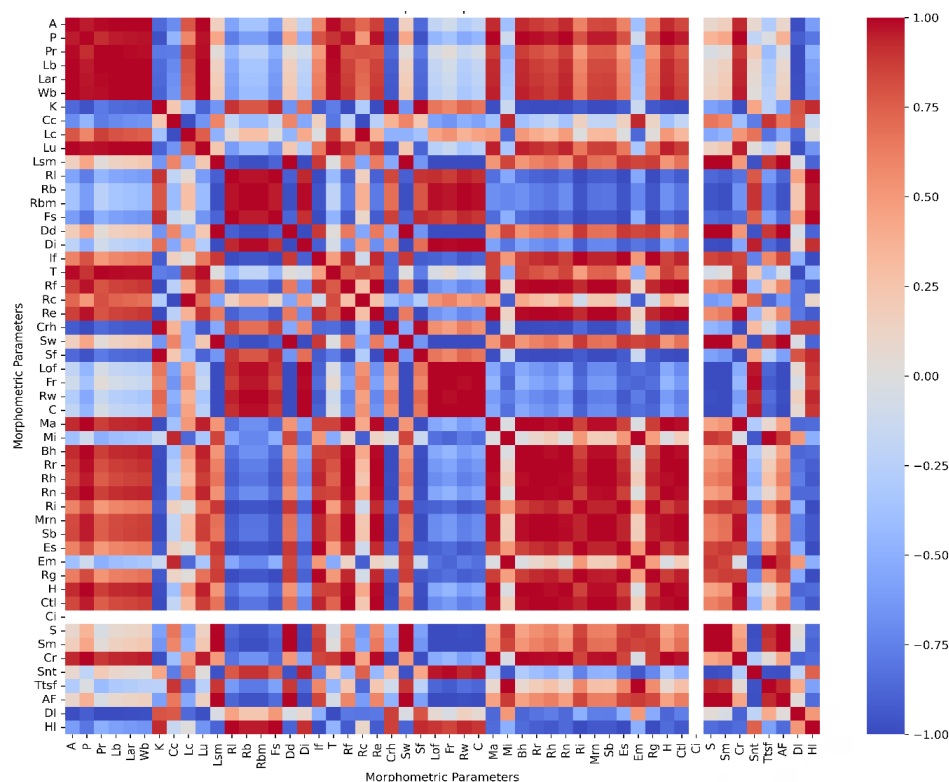


Table 6. Summary of Most Affected Morphometric Parameters Post-Avulsion, Categorized by Type

Parameter Type	Most Affected Parameters	Interpretation
Linear	Lb, Dd, Rb	Stream length/number reduced post-avulsion
Areal	A, Cc, P	Shape and size altered due to re-routing
Relief	Cr, Rr	Elevation differences more pronounced in AMW
Tectonic	Ctl, AF, HI	Indicates morphotectonic decoupling

Planning and Hydrological Implications

The morphometric divergence between the Current and Abandoned Mahananda Watersheds reveals critical insights for regional planning. The abandoned basin, with reduced relief and drainage density, suggests declining runoff and increased susceptibility to water stagnation, localized flooding, and agricultural stress—especially during peak monsoon events. Conversely, the current basin exhibits active fluvial characteristics, with steeper slopes, higher stream connectivity, and greater sediment transport potential. This requires focused flood control, bank stabilization, and sediment management, particularly near the present-day Ganga confluence at Bhutni Island. These findings provide a valuable morphometric baseline to inform flood risk assessment, watershed management, and land use planning across the transboundary Mahananda Basin.

CONCLUSIONS

This study investigates the morphometric consequences of channel avulsion in the lower Mahananda River Basin, a transboundary fluvial system spanning Nepal, India, and Bangladesh. By delineating and comparing the Old Mahananda Basin (OMB), the Current Mahananda Watershed (CMW), and the Abandoned Mahananda Watershed (AMW), we provide quantitative insights into how avulsion reshapes basin morphology and alters watershed function.

Results reveal a marked divergence between the two post-avulsion basins. CMW maintains moderate relief, channel connectivity, and hydrological activity, whereas AMW exhibits pronounced functional decay—characterized by steep declines in stream length, drainage density, basin relief, and slope complexity. These changes point to the abandonment of hydrological function and a shift toward a geomorphically inactive landscape in AMW. Tectonic asymmetry indicators, such as the Asymmetry Factor (AF) and Transverse Topographic Symmetry Factor (TTSF), along with dimensionality-reduction outputs (PCA, clustering), confirm the influence of structural tilting in initiating and shaping post-avulsion evolution.

The study also demonstrates the methodological strength of integrating multi-resolution DEMs, georeferenced historical maps, and statistical tools to trace fluvial landscape change over time. Such an approach offers a replicable framework for morphometric assessment in dynamic alluvial settings, particularly in regions where tectonic activity and anthropogenic interventions intersect. In terms of planning implications, the contrasting morphometric behavior of CMW and AMW has direct

relevance for flood management, land use zoning, and conservation strategies. The findings provide a morphometric baseline to inform watershed management in structurally sensitive, monsoon-fed basins. While the study is limited to topographic and morphometric data, future research may incorporate hydrological modeling, field-based sediment analysis, and climate sensitivity assessments to extend the understanding of avulsion-driven basin evolution.

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Assessment of Conservation Practices and Threats to Wildlife Management in Jos Wildlife Park, Nigeria

ABSTRACT

The conservation of biodiversity presents a global challenge that requires coordinated action across spatial and governance scales, including local, national, and international levels. Wildlife parks, though often less formally protected than national parks, play a vital role in preserving biodiversity and sustaining ecosystem services. However, many are increasingly threatened by human encroachment, including urbanization, agriculture, and mining, which degrade habitats and undermine ecological integrity. This study assessed conservation practices and threats to biodiversity management in Jos Wildlife Park, Nigeria, through an integrated approach combining two decades of Landsat-derived Normalized Difference Vegetation Index (NDVI) analysis, Google Earth image processing, field surveys, and stakeholder interviews. Results showed that NDVI values were consistently higher in the park's core than in its edge and buffer zones, indicating greater vegetation health at the center. However, declines in vegetation cover toward the park's periphery reflected significant pressures from surrounding human activities. Field and interview data further revealed limited conservation practices, with challenges in stream and pond management, habitat restoration, and enforcement against illegal activities. Major threats included agricultural encroachment, poaching, and illegal logging, compounded by resource shortages and governance constraints. These findings highlight the urgent need for targeted habitat restoration, strengthened law enforcement, and enhanced management capacity to safeguard Nigeria's urban conservation areas and support the country's commitment to the global "30 × 30" biodiversity framework.

Keywords: biodiversity, Jos Wildlife Park, urban conservation, habitat degradation, remote sensing

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Data Availability Statement: The data used in this study to analyze vegetation changes within Jos Wildlife Park and the surrounding areas (2000–2021) is archived at 10.6084/m9.figshare.25447183. Field survey data and interview transcripts are available upon request from the corresponding author.

INTRODUCTION

Biodiversity conservation is a global priority, vital for sustaining human wellbeing and ecosystem health. Legally designated protected areas, such as national parks, play a central role in safeguarding biodiversity and maintaining ecosystem services. However, other potential conservation spaces, including wildlife parks and urban green areas, also make essential contributions through habitat preservation, recreation, and environmental education (Ives et al., 2016). Although these areas often lack formal protection status, they significantly support local conservation efforts by sustaining native species and ecological processes (Ives et al., 2016; Crowley et al., 2020).

The urgency of conserving biodiversity is heightened by the global extinction crisis, with over 47,000 species now listed as threatened on the IUCN (International Union for Conservation of Nature) Red List of Threatened Species (IUCN, 2025). In Nigeria alone, more than 10% of assessed species (approximately 500 species) face extinction risks (Danmallam et al., 2024a). The Kunming–Montreal Global Biodiversity Framework, adopted at the Convention on Biological Diversity’s COP15 in 2022, sets ambitious goals to halt this trend, including protecting 30% of the world’s land and sea areas and restoring 30% of degraded ecosystems by 2030—the “30 by 30” target (Convention on Biological Diversity [CBD], 2022). Achieving these objectives demands adaptive, sciencebased management strategies that respond to local threats while promoting equity, sustainability, and long-term effectiveness.

Many conservation areas, particularly those located in urban and periurban environments, play an increasingly important role in biodiversity protection, recreation, and tourism. These spaces provide essential habitats for a wide variety of plant and animal species, support ecological stability, and deliver cultural and economic benefits to surrounding communities (Agbelade et al., 2016; Ives et al., 2016; Crowley et al., 2020). However, they are under growing pressure from human activities such as urban expansion, deforestation, and agricultural encroachment, which degrade habitats and undermine ecosystem integrity (Chaskda & Fandip, 2017; Danmallam et al., 2024b). These challenges are further compounded by limited resources for effective management and enforcement, as well as by the escalating impacts of climate change (Fada et al., 2022). Together, these factors threaten the longterm sustainability of biodiversity within these landscapes.

Remote sensing tools, particularly the Normalized Difference Vegetation Index (NDVI), have proven valuable for monitoring vegetation health and detecting human impacts on ecosystems (Safaei et al., 2023; Soubry et al., 2021). NDVI provides reliable insights into habitat trends over time and, when paired with field assessments and stakeholder perspectives, offers a robust framework for evaluating conservation effectiveness (Baldwin et al., 2018; Brumm et al., 2022; Crowley et al., 2020). However, little research has addressed the specific conservation challenges faced by Nigerian wildlife parks, especially those located in rapidly urbanizing landscapes such as Plateau State. This study addresses that gap by evaluating conservation practices and identifying key threats to biodiversity management in Jos Wildlife Park. Specifically, we aimed to:

- quantify spatiotemporal changes in vegetation cover across the park's core, edge, and buffer zones;
- document existing conservation practices and their implementation;
- identify and map major human-induced threats, including urban expansion, agriculture, and mining; and
- assess stakeholder perceptions and institutional challenges influencing conservation outcomes.

By integrating NDVI analysis with field surveys and stakeholder interviews, this study provides practical insights to strengthen biodiversity protection and enhance the longterm sustainability of Jos Wildlife Park within the broader context of Nigeria's commitments to the "30 × 30" target.

METHODS

Description of the Study Area

Jos Wildlife Park lies within the Jos North Local Government Area of Plateau State, Nigeria. Its coordinates range from latitude 9°53'02" N to 9°53'10" N and longitude 8°50'45" E to 8°51'08" E. The park covers approximately 8 km² and is located along Miango Road (Chaskda & Fandip, 2017). Established in 1972, Jos Wildlife Park is managed by the Plateau State Tourism Corporation. Since its founding, the park has become a prominent attraction, drawing tourists from across the country.

Jos Wildlife Park serves as a critical refuge for diverse fauna and flora species, both *ex-situ* and *in-situ*. Notably, it houses carnivores such as *Panthera leo* (lion), reptiles such as *Python sebae* (rock python), large birds such as *Leptoptilos crumeniferus* (marabou stork), primates such as *Papio* spp. (baboon), and mustelids such as *Mellivora capensis* (honey badger). The park is surrounded by communities including Ikkukumu of Tudun Wada, Sabon Gari of Mado, the State and Federal Low-Cost Housing of Rantya, and Dong (Figure 1). These communities have experienced significant growth in recent years due either to rapid urbanization or to resettlements resulting from conflicts. Consequently, their continuous expansion poses a threat to both the flora and fauna of Jos Wildlife Park.

Data Collection and Analysis

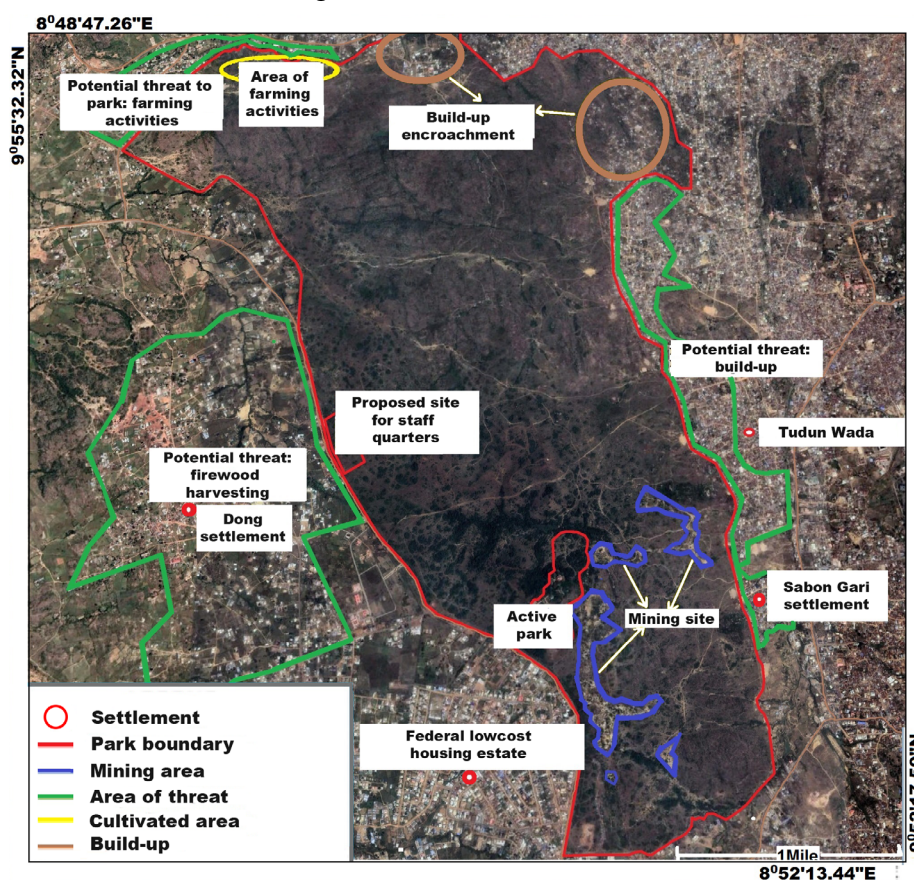
We combined field survey data with satellite imagery to analyze biodiversity conservation practices in Jos Wildlife Park. We used Google Earth Engine (Gorelick et al., 2017) to access and process NDVI data from the Landsat 7 satellite sensor. Landsat 7 provides a 30 m spatial resolution in the red and near-infrared bands used to calculate NDVI, making it suitable for large-scale vegetation and land cover monitoring (Gong et al., 2013).

We used the LE07_L1TP product, which provides surface reflectance values after atmospheric correction. To remove cloud-contaminated pixels, we applied a cloud-mask function based on the quality assessment band (BQA) of the LE07_L1TP product. We extracted the average NDVI values for Jos Wildlife Park and its surrounding areas: a 200-meter buffer zone, a 200-meter edge zone

extending inwards from the park boundary, and the remaining core areas, for each 5year interval from 2001 to 2020, using the GEE feature collection and reducer functions.

We calculated the NDVI values for each image as the difference between the near-infrared and red reflectance, divided by their sum. We then exported the NDVI values as a CSV file and imported them into R for further analysis and visualization. The *ggplot2* library was used to visualize the NDVI data (Figure 2) and to create boxplots depicting NDVI values for the park's core, edge, and buffer zones across the years.

Figure 1. Jos Wildlife Park and Surrounding Areas (Settlements, Potential Threats and Encroachment Activities)



Model Specification

We analyzed the relationship between NDVI, spatial sections of the park, and temporal variation using the following regression model in R statistical software (R Core Team, 2023), which examines the effects of Section (Core, Edge, Buffer) and Year on NDVI:

$$NDVI_{ij} = \beta_0 + \beta_1 \text{Section}_i + \beta_2 \text{Year}_j + \epsilon_{ij}$$

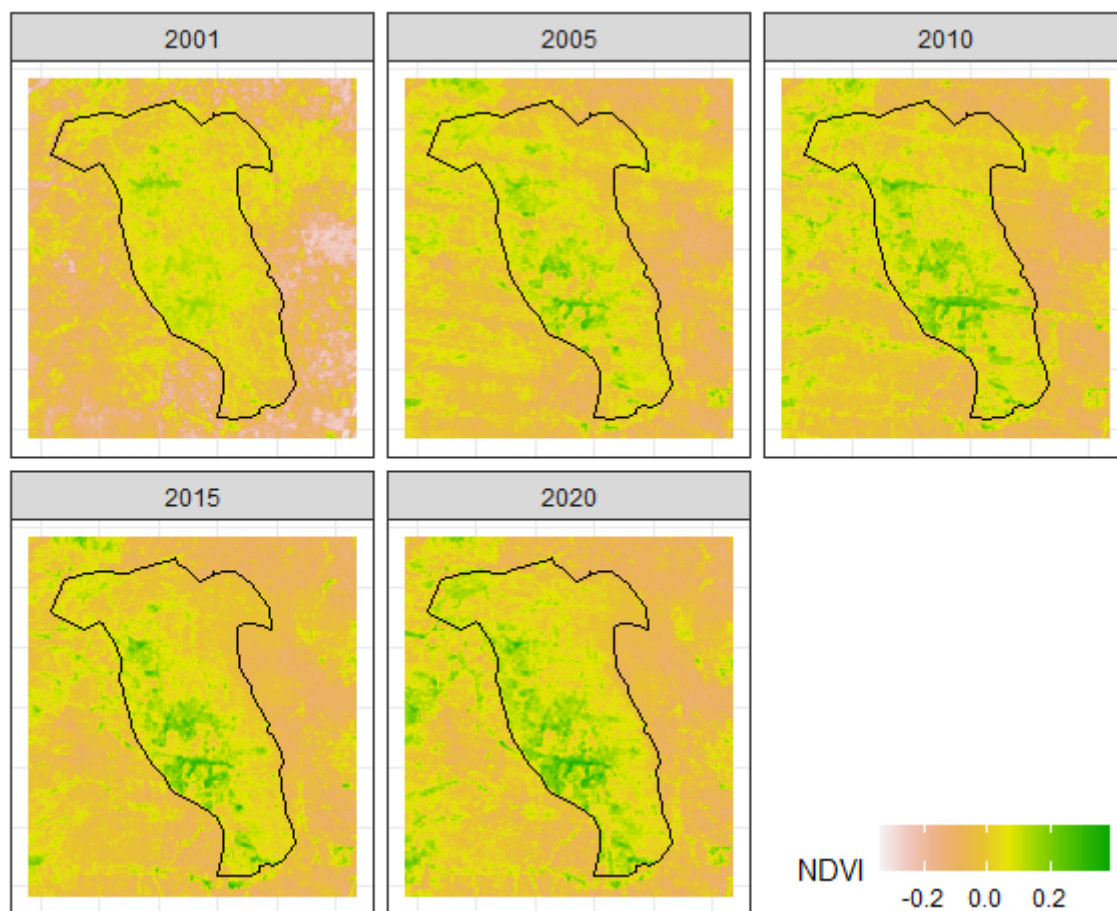
Where $NDVI_{ij}$ is the vegetation index for Section i in Year j .

β_0 is the intercept.

β_1 and β_2 represent the coefficients for Section and Year, respectively.

ϵ_{ij} denotes the residual error.

Figure 2. Spatio-Temporal Changes in NDVI (Normalized Difference Vegetation Index) From 2001 to 2020 at 5-Year Intervals in Jos Wildlife Park



Furthermore, two high-resolution images ($4,800 \times 4,800$ pixels) were obtained from Google Earth Pro (2022). These include a historical image from November 2001 and a recent image from November 2021, both covering the area encompassing Jos Wildlife Park. The images were used to assess landuse change over time and to evaluate the increasing threat of urbanization to the park. They were imported into ILWIS 3.7 GIS software, georeferenced, and analyzed to detect land use transitions. These included the conversion of park vegetation to built-up areas, cultivated lands, illegal mining sites, and others.

During the field survey phase, reconnaissance surveys were carried out for proper familiarization with the park environment. The survey enabled firsthand observation of the animals in the park, the activities of staff, and the general operations at the park. Some of the animals observed in the park included the African savanna elephant (*Loxodonta africana*), lion (*Panthera leo*), common ostrich (*Struthio camelus*), olive baboon (*Papio anubis*), spotted hyena (*Crocuta crocuta*), marabou stork (*Leptoptilos crumeniferus*), Thomson's gazelle (*Gazella thomsonii*), spurred tortoise (*Centrochelys sulcata*), African rock python (*Python sebae*), and capuchin monkey (*Cebus spp.*). Some individuals were allowed to roam freely outside their enclosures during the survey period. Other animals sighted

included the Nile crocodile (*Crocodylus niloticus*), mallard ducks (*Anas platyrhynchos*), greylag geese (*Anser anser*), and West African dwarf goats (*Capra hircus*).

To collect survey data, three research assistants were recruited and trained between March and August 2019 for the study. A convenience sampling technique was used to collect quantitative data through oral interviews conducted with eleven key informants, comprising managerial staff at the administrative level as well as park keepers at Jos Wildlife Park. The interview schedule included both open-ended and closed-ended questions to explore insights into the ecological context, conservation practices and priorities, perceived effects of conservation efforts, the impact of urbanization and other human activities on biodiversity sustainability, emerging threats, and biosafe measures for biodiversity conservation. Data collected from the field were sorted and coded for analysis using Excel in Microsoft Office 2016. Further analysis utilized descriptive statistics, with the results presented as percentages through graphs and charts.

RESULTS

Wildlife Conservation Practices Observed in Jos Park

Five methods of habitat management were identified as common practices in the park. These were field borders, filter strips, riparian forest buffers, stream habitat improvement and management, and pond management (Figure 3).

Field Border: Field borders in Jos Wildlife Park are managed primarily through mowing and weed control. Approximately 73% of respondents confirmed regular mowing, and 45% reported that livestock are excluded during the nestling season to support wildlife. Perennial grasses are planted along open areas to provide cover and movement corridors. However, 66% indicated that reshaping or reseeding of areas damaged by storms or equipment is rarely practiced, likely due to the infrequency of such disturbances.

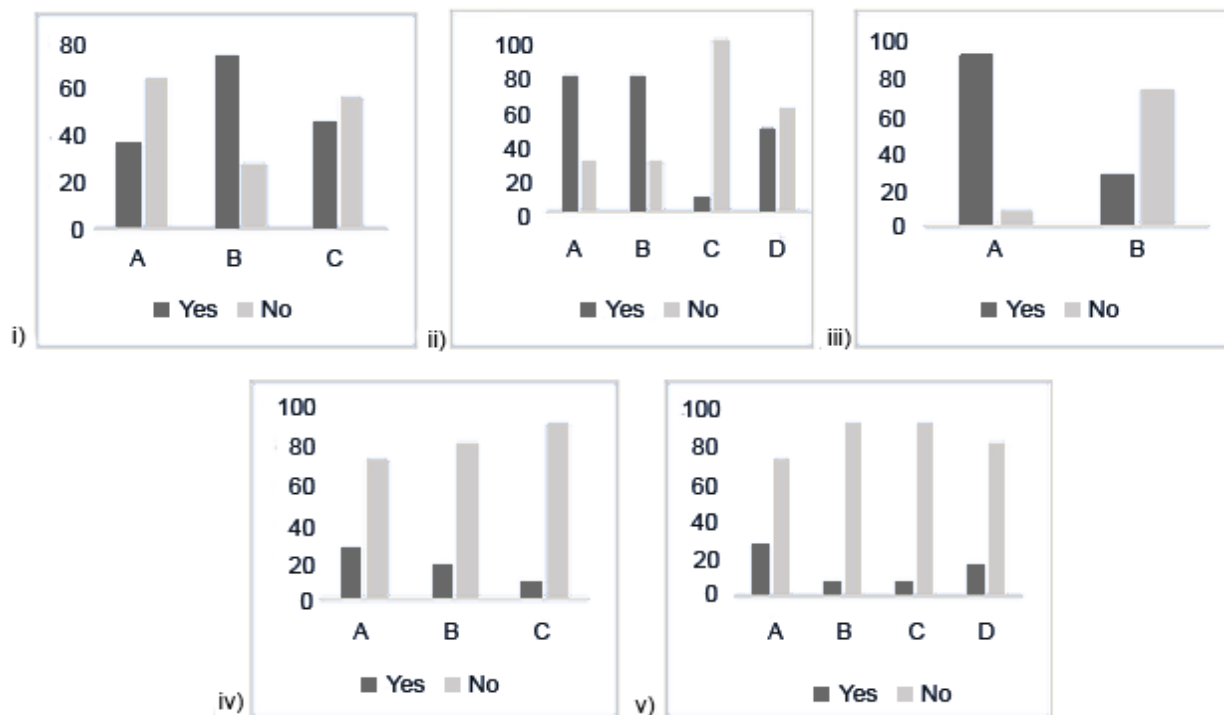
Filter Strip: Filter strips are employed to reduce runoff and improve water quality. While 73% of respondents reported regular weed control and prescribed burning, 91% noted that these strips do not effectively manage concentrated flows. Additionally, 55% stated that nutrients are not supplemented as needed. Field visits revealed weed-free areas during the dry season, but also poorly maintained, turbid water bodies.

Riparian Forest: The Park maintains some tree cover along streams, supporting water quality and facilitating wildlife movement. However, active riparian management appears to be limited.

Stream Habitat Improvement and Management: Stream habitats are poorly managed, with 73% of respondents stating that inspections are not conducted routinely, and 82% reporting that bank or bed instability is not promptly addressed. Furthermore, 91% indicated that in-stream structures are not evaluated annually. Many water bodies were observed to be stagnant, polluted, or dried up, which may explain the low presence of wildlife.

Pond Management: Pond conditions are suboptimal. Livestock are not excluded (82%), aquatic species are not restocked (91%), and weed control is minimal. Additionally, 73% noted that water drawdown to manage pollution is not practiced. These shortcomings likely contribute to poor water quality and ecological imbalance.

Figure 3. Conservation Practices Observed in the Jos Wildlife Park



i) Field Border (A=Shaping and reseedling of areas damaged by storms, animals, chemical tillage or equipment traffic. B=Mowing and control of weed development. C=Protection of livestock during nestling season to maximise wildlife benefit). **ii) Filter Strip** (A=Controlling undesired weeds. B=Prescribed burning with an approved burn plan. C=Prevention of concentrated flows through the filter strip application of nutrient supplements where needed). **iii) Riparian Forest Buffer** (A=Periodic pruning of trees. B=Periodic harvesting of trees). **iv) Stream Habitat Improvement and Management** (A=Periodic inspection of streams, B= Prompt repair of stream banks or streambed instability, C=Annual evaluation of in-stream structural measures). **v) Pond Management** (A=stock exclusion to maintain water quality. B= Stock aquatic life as recommended in plan. C= Control of aquatic weed. D= Control of aquatic population).

Spatial Temporal Distribution of NDVI in the Jos Wildlife Park

We found that both park section and year had significant positive effects on NDVI ($p < 0.01$). NDVI was highest in the Core Area, showing a decreasing gradient toward the Edge and Buffer Zones (Figure 4). Specifically, NDVI in the Core Area was, on average, 0.08 higher than in the Buffer Zone, while the Edge was 0.05 higher than the Buffer Zone. Additionally, year had a significant positive effect ($\beta = 0.00142$, $p < 0.01$), indicating a consistent increase in NDVI over time. NDVI remained lowest in the Buffer Zone, suggesting potential impacts of encroachment and development activities

in the surrounding area on the park. Detailed parameter estimates, including standard errors, confidence intervals, and *p*-values, are presented in Table 1.

Figure 4. Boxplots of NDVI Values for the Buffer, Edge and the Core Areas of the Park Across the Years

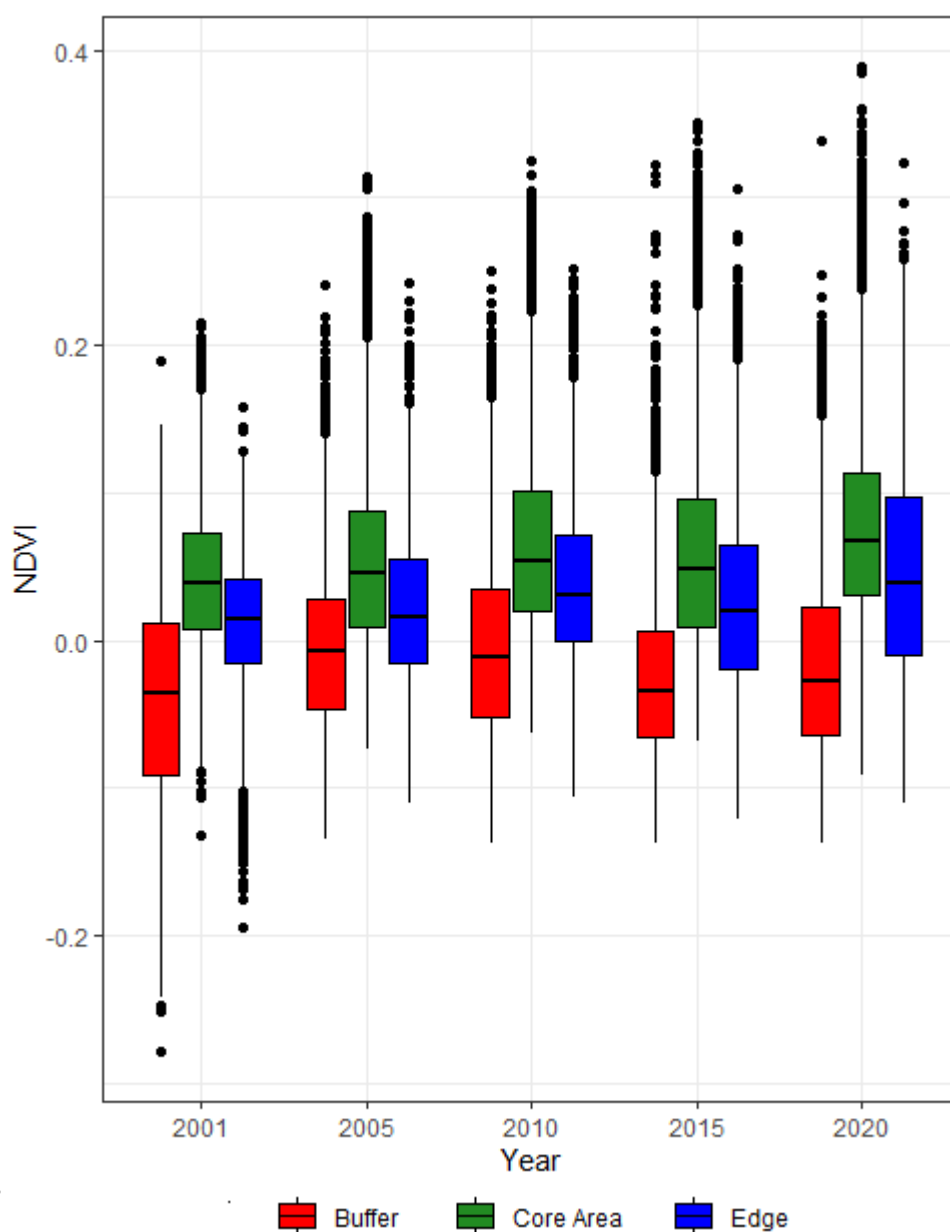


Table 1. Estimated Effects of Park Section and Year on NDVI in Jos Wildlife Park

Parameter	Coefficient	SE	95% CI	t(95626)	<i>p</i>
(Intercept)	-2.87	0.06	(-2.98, -2.76)	-50.08	< .001
Section (Core Area)	0.08	4.81e-04	(0.08, 0.08)	161.81	< .001
Section (Edge)	0.05	5.84e-04	(0.05, 0.05)	80.44	< .001
Year	1.42E-03	2.85e-05	(1.36e-03, 1.48e-03)	49.82	< .001

Threats to Conservation Practices in Jos Wildlife Park

Based on the five most common conservation practices observed in Jos Wildlife Park, we further integrated results from the analysed satellite images with responses from the interviews conducted to ascertain the threats to conservation practices in the area.

Encroachment of human activities into the park and surrounding areas: Results from imagery analysis revealed evidence of threats due to the encroachment of human activities into the park area. These threats include pockets of illegal mining activities, the spread of built-up areas, and evidence of cultivation within the park (Figure 5). To determine the extent of these three categories of encroachment activities, satellite images from 2001 and 2021 were compared.

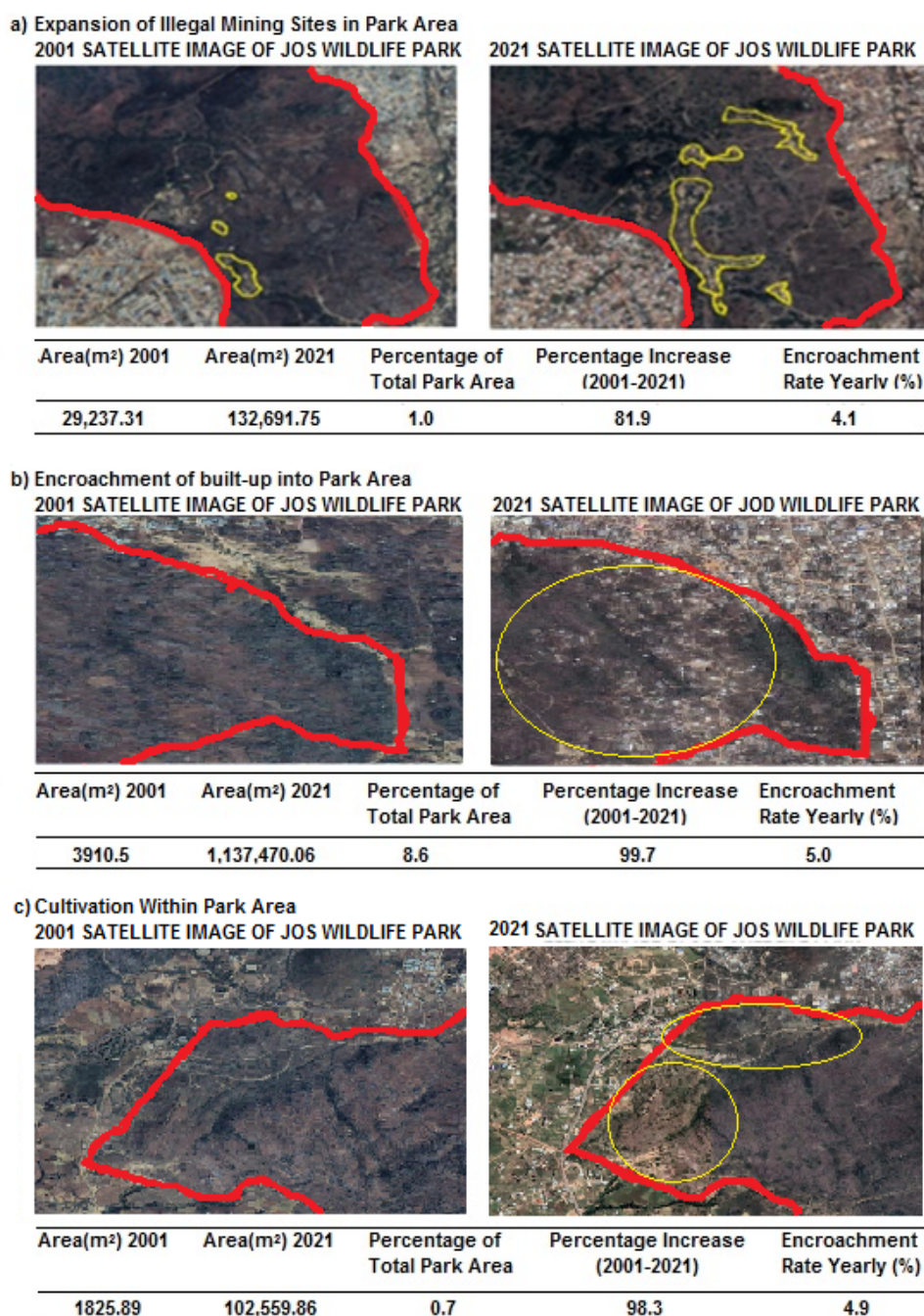
- Analysis of illegal mining activities: Results revealed that in 2001, approximately 29,237 m² of park land was affected by illegal mining activities. By 2021, this area had increased to 132,691 m², representing an average annual encroachment rate of 4.1%.
- Analysis of built-up areas: Results showed that in 2001, only 3,910 m² of park land showed evidence of built-up development. By 2021, this figure had risen to over 1,137,470 m², with an average annual encroachment rate of 5% of the current built-up area.
- Analysis of cultivation: In 2001, about 1,825 m² of park land was recorded as being under cultivation. However, by 2021, this area had expanded to 102,559 m², with an average annual encroachment rate of 4.9%.

Of the three categories of encroachment activities, the expansion of built-up areas showed the most significant increase. This period of growth coincides with a time of civil unrest in the state and surrounding regions, which contributed to the spread of unplanned urban development.

Threats to conservation due to underlying factors: This study identified six underlying factors posing threats to conservation practices in the Park, namely: (a) high population growth rate, (b) poverty, (c) constraints related to government policy and legislation, (d) poor land use planning, (e) issues of governance and transparency, and (f) the socio-cultural characteristics of adjoining settlements (Figure 6). Results revealed that the majority of respondents (50% and above) agreed that these six factors constitute threats to conservation in the Park. However, respondents did not consider climate change to be a threat.

Habitat degradation as a threat to conservation in Jos Wildlife Park: Findings reveal that agricultural practices, the harvesting of biological resources, and the activities of extractive industries were identified as major causes of habitat degradation, posing a significant threat to conservation in Jos Wildlife Park. Over 40% of respondents confirmed this (Figure 7).

Figure 5. Threats to Jos Wildlife Park and its Surroundings Based on Spotted Human Activities



Natural resource harvesting as a threat to conservation in Jos Wildlife Park: Natural resource harvesting was identified as a key threat to conservation in Jos Wildlife Park. This threat was categorized into nine classes, of which eight were considered significant by respondents, while one was not (Figure 8). Ranked from most to least frequently reported, the threats include poaching, illegal logging, bushfires, overgrazing, pollution, unsustainable harvesting of non-timber products, uncontrolled and illegal mining practices, and fuelwood consumption. Interestingly, invasive species were not perceived as a threat by respondents.

Figure 6. Underlying Factors to Poor Conservation Practices in Jos Wildlife Park

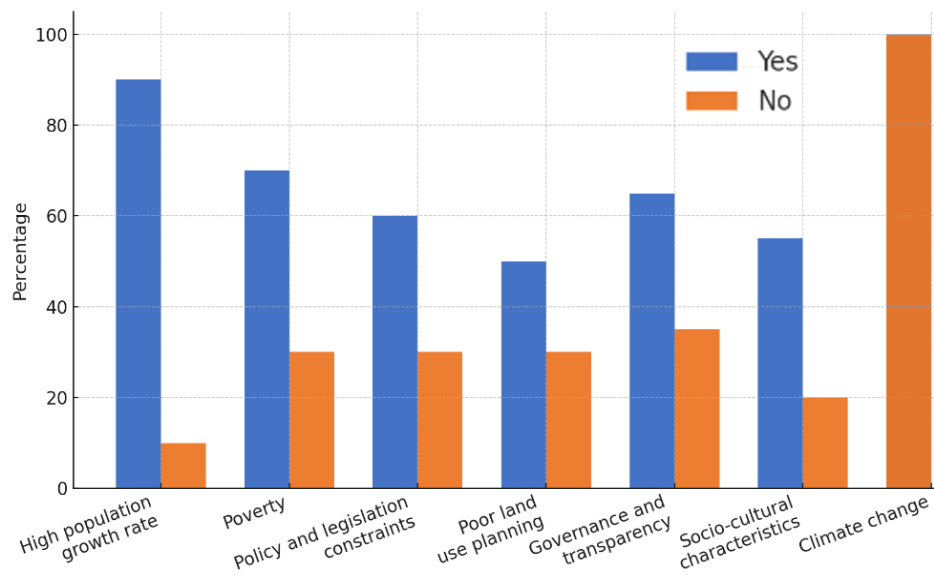


Figure 7. Habitat degradation activities in Jos Wildlife Park

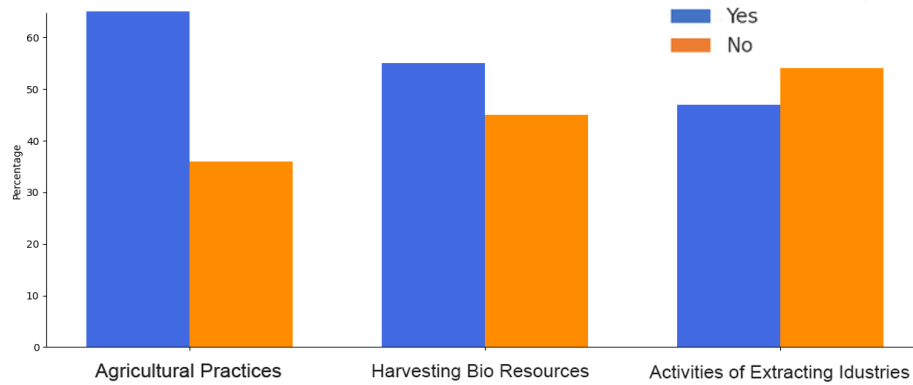
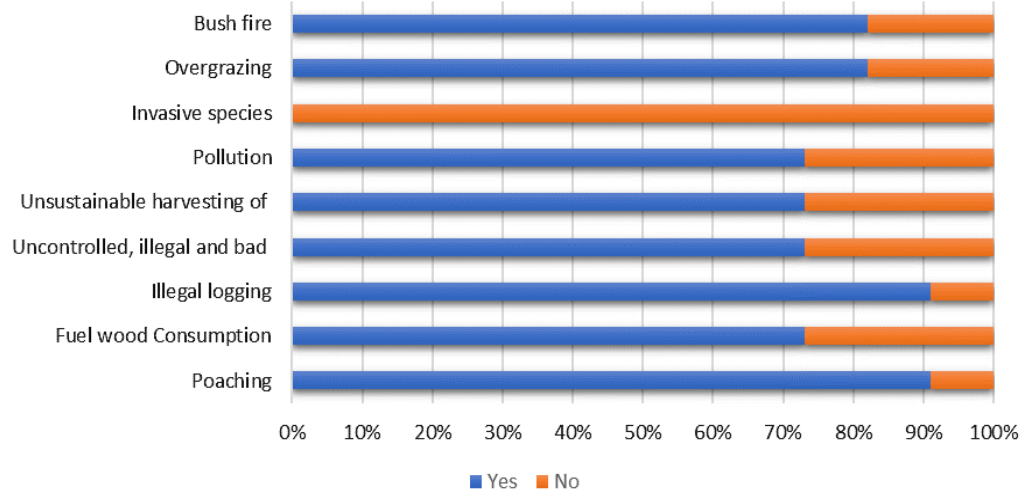


Figure 8. Threats of Natural Resources Harvesting in Jos Wildlife Park



CONCLUSIONS

Our study revealed that the core areas of Jos Wildlife Park exhibited higher and increasing NDVI values compared to its edge and buffer zones, highlighting the park's effectiveness in conserving vegetation relative to surrounding areas. This finding corroborates prior research showing that protected areas can enhance vegetation cover and quality while mitigating the impacts of land-use change and climate-induced degradation (Geldmann et al., 2013; Pulido-Chadid et al., 2023).

Temporal variations in NDVI differences between the park and its edge and buffer zones suggest that the park remains vulnerable to external pressures, including urbanization, agriculture, and mining. Similar patterns have been documented in other urban and peri-urban protected areas, where encroachment from human settlements and extractive activities reduces ecological integrity (Chaskda & Fandip, 2017; Azila et al., 2024). These findings underscore the broader challenge of balancing urban expansion with biodiversity conservation (Safaei et al., 2023; Glied & Barkóczi, 2013). Our results emphasize the need for enhanced management and monitoring strategies within both the park and its buffer zones to safeguard vegetation and biodiversity over the long term (Baldwin et al., 2018; Brumm et al., 2022).

Although mowing and prescribed burning are practiced, limited stream and pond management weakens ecological integrity (Crowley et al., 2020; Brumm et al., 2022). Agricultural encroachment, bioresource harvesting, and weak enforcement remain major drivers of habitat degradation (Ives et al., 2016). Poaching and illegal logging were identified as the most severe threats, echoing broader patterns of unsustainable resource use.

Persistent gaps in staffing, funding, and enforcement capacity further constrain effective management (Urbano et al., 2024). Without urgent interventions, the park risks continued biodiversity loss. Strengthening financial and institutional support, enhancing monitoring, and adopting globally recognized conservation practices are critical to securing the park's long-term sustainability and its contributions to local livelihoods and national biodiversity goals. These actions would also support Nigeria's commitment to the Convention on Biological Diversity's 30 by 30 target of protecting 30% of land and sea areas by 2030 (CBD, 2022), positioning Jos Wildlife Park as a key contributor to global biodiversity conservation.

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