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Review papers

Impacts of land use land cover change and climate change on river hydro-morphology- a review of research studies in tropical regions

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ABSTRACT

Tropical regions have experienced the fastest Land Use Land Cover Change (LULCC) in the last decades, coupled with climate change (CC) this has affected the hydrological and geomorphological processes of river systems. With the increased demand for land, the general trend has been the loss of forest land to agriculture and settlements. These changes have altered the water balance components through enhanced or reduced evaporation, peak flow, flooding, and river morphology. The aim of this review paper is to provide a *meta*-analysis on the effects of spatiotemporal changes in climate and LULC on river hydro-morphology in the tropics. Following a systematic search, 60 case studies were identified, of which the majority (68%) experienced forest loss due to agricultural and urban expansion, resulting in increased streamflow, surface flow, and total water yield and decreased ET and groundwater recharge. 12% of the case studies showed the impacts of LULCC on channel morphology features through sediment transport and riverbank erosion. Results from this study show limited correlation between LULCC and hydrological variables, indicating that there are likely other factors controlling hydrological processes. Catchment heterogeneity including soil and topography play an important role. Based on studies that project these changes into the future, similar trends are expected over the next decades, with differences based on LU and climate scenarios. There are still limited studies on river hydro-morphology responses to LULCC and CC in the tropics despite the major changes taking place there. In light of future changes, more studies are needed to improve our understanding.

1. Introduction

It has been estimated that about 17% of the Earth's land surface has changed at least once between 1960 and 2019, resulting in a global forest loss of 0.8 million km^2, and 1.0 million km^2 increase of agricultural land, among other changes (Winkler et al., 2021). These widespread Land Use Land Cover Changes (LULCC) mainly attributed to human causes (anthropogenic) affect watershed hydrologic systems in diverse ways (Bridgewater et al., 2018), primarily through the alteration of rainfall and runoff processes (Gebremicael et al., 2019). Furthermore, they contribute to changes in river channel morphology through soil erosion and deposition (Chuenchum et al., 2020; Maaβ et al., 2021). Along with these anthropogenic factors, climate change (CC) influences the intensity and frequency of rainfall and temperature (Koneti et al., 2018) which have direct effects on quantities of evapotranspiration (ET) and runoff. According to IPCC-AR6 (2021), since the 1970s, each decade has been successively warmer than the preceding one, mainly due to anthropogenic Green House Gas (GHG) emissions resulting from economic and population growth. Furthermore, CC will likely intensify these changes (rainfall and temperature patterns) in the future leading to increased frequency of extreme hydrologic events (IPCC-AR6, 2021; IPCC, 2014).

The tropics have experienced the fastest rate of LULCC, especially deforestation, with estimates of 8.0 million ha/year in the 1990s and 7.6 million ha/year in the 2000s (Achard et al., 2014). The tropics lost 11.1 million hectares of tree cover in 2021 (Liz & Mikaela, 2022). These changes were largely driven by demographic and socio-economic growth (Gashaw et al., 2018). The pressure exerted on tropical river basins, due to LULCC, has been steadily increasing over recent decades (Farinosi et al., 2019; Naomie, 2020; Wiejaczka et al., 2014). Agriculture has been the dominant force driving LULCC in the last century, with more than half of all new agricultural land in the tropics converted from forest between 1980 and 2000 (Lambin & Meyfroidt, 2011).

River hydro-morphology describes the hydrological and

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geomorphological processes and properties of a river system, their interactions, and their spatial distribution and variability (JBA, 2021). It deals with physical processes determining river behavior (Hajdukiewicz et al., 2017), and the resulting configurations or morphology. LULCC translates into changes in the water balance components through enhanced or reduced evaporation, peak flow, and flooding (Teklay et al., 2021). Additionally to LULCC, changes in water balance components, such as peak flows (quantity, timing, and duration), impact morphological properties (Langat et al., 2020). Land cover plays an important role in these processes, as it defines the soil state. The magnitude of these effects depends on the watershed characteristics, including the size, extent of change, topography, soil characteristics, and weather conditions (Allan et al., 1997; Moraes et al., 2018).

Fig. 1 illustrates the interrelations between these different components. LULCC and CC are inter-linked, as changes in land cover affect the atmospheric energy balance, which influences rainfall and temperature patterns, while at the same time LULC is affected by changes in weather patterns. The same feedback mechanism exists between LULC and catchment hydrology, as well as on river morphology. Climate change and hydrology have one-way effects on river morphology.

Understanding the watershed hydro-morphological responses to changes in both climate and LULC –especially in tropical regions where rainy seasons are followed by dry seasons (Gomes et al., 2021)— is vital for effective and sustainable land and water resources management. Despite extensive reviews on the effects of LULCC and CC on basin hydrology, there is limited focus on both morphological and hydrological feedbacks in tropical regions. Focusing on the tropics, we undertook a *meta*-analysis of existing studies analyzing these aspects, in order to better understand the effects of spatiotemporal changes in climate and LULC on river hydro-morphology. An overview of the LULCC transitions in the region is provided. Process steps to identify relevant research publications related to this topic are outlined including both empirical research and simulation modelling works. Subsequently we provide an overview of the associated historical and potential future impacts of the LULCC and CC on river hydro-morphology.

2. Literature review: LULCC impacts on river hydro-morphological processes

2.1. LULC transitions and their impacts on hydrological components

Water balance is at the heart of all hydrological processes that occur in a watershed (Akpoti et al., 2016). CC affects the rainfall and temperature patterns (Chuenchum et al., 2020), while LULCC affects how

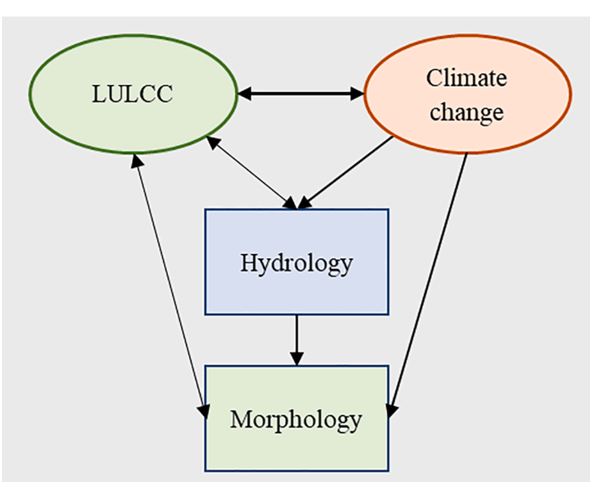

Fig. 1. LULCC, CC, hydrology, and morphology inter-relations. Arrows represent the direction of causality.

the watershed responds to rainfall by altering different components of the water balance, including rates of interception, infiltration, evapotranspiration, and groundwater recharge rates (Santillan et al., 2019). Consequently, LULCC affect the timing and amount of surface runoff (Baker & Miller, 2013). In this section, we summarize the mechanisms that underlie the changes in hydro-morphology of tropical catchments in response to LULC transitions. LULC categories considered include forests, agriculture, urban areas, degraded land, and pastureland. The LULC transitions investigated in this paper and their impacts on the water balance components are illustrated in Fig. 2.

Forest is known to consume a lot of water through evapotranspiration –trees water consumption, and promote groundwater recharge (Aladejana et al., 2018; Tan et al., 2015). The forest deep roots serve as flow paths for recharging the ground water and increase the base flow (Farinosi et al., 2019; Ogden et al., 2013). In addition, forest increases the infiltration rate and improves the water holding capacity of the soil (Obahoundje et al., 2018; Zhang et al., 2019). Therefore, deforestation decreases the infiltration processes due to a decrease in soil permeability, less rainfall interception, leading to an increase in runoff, decrease in baseflow, and less ground water recharge (Naha et al., 2021; Olang et al., 2011). Conversely, afforestation has been linked with reduced river streamflow and water yield, as a result of increased evapotranspiration (Aragaw et al., 2021).

Agriculture practices can lead to soil crusting which reduces the soil infiltration rate (Teklay et al., 2021). Cultivated land is prone to surface runoff generation (Näschen et al., 2019), since the land is less covered at the beginning of the rainy season (Bekele et al., 2018), therefore, there is more rapid conversion of rainfall to runoff (Naha et al., 2021). Dias et al. (2015) found that the streamflow in soy catchments was about three times greater than that of forest catchments in Brazil. The expansion of cultivated land at the expense of natural vegetation, tends to decrease soil and water storage, thus, decreases the rainfall infiltration rate, and leads to an increase in surface flow (Sinha & Eldho, 2018; Sulamo et al., 2021), as well as the rate at which it reaches the stream network (Getu Engida et al., 2021; A. Horton et al., 2021). Additionally, the absence of deep rooting system and extensive canopies, leads to less ET and groundwater recharge, and amplifies runoff (Das et al., 2018; Koneti et al., 2018).

Urban expansion is associated with an increase in impermeable areas, hence, decreasing the infiltration and groundwater recharge rates, associated with an increase in runoff conveyance and flow peaks (Akpoti et al., 2016; Viola et al., 2014). The extension of built-up areas in place of natural vegetation cover, alters the water resources through changes in biophysical properties e.g. vegetation canopy cover (Getu Engida et al., 2021).

Pastureland extension tends to decrease the infiltration rate due to soil compaction by grazing, thus, increasing the surface runoff and the streamflow magnitude (Hassaballah et al., 2017; Hengade & Eldho, 2019). As a result of soil compaction, higher proportion of rainfall is being converted into surface runoff, instead of infiltrating the soil and contributing to groundwater (GW) recharge (Baker & Miller, 2013).

In summary, large-scale transition of tropical forest to non-forest land affects the water cycle. It decreases infiltration and interception, increases surface runoff, and significantly decreases the evapotranspiration and groundwater recharge. Therefore, the compacted bare soil exposed to intense rainfall increases the discharge rate rapidly and suddenly, increasing flood risk (A. J. Horton et al., 2021; Sugianto et al., 2022). Moreover, deforestation impacts atmospheric water input, causing more intense dry seasons, which exacerbates drought risks (Qi et al., 2020; Staal et al., 2020).

2.2. River morphology responses to LULCC

According to OFB (2010), there exist two morphological factors of a river, control factors –including water discharge and sediment load, and response factors –river planform and channel cross-section. The

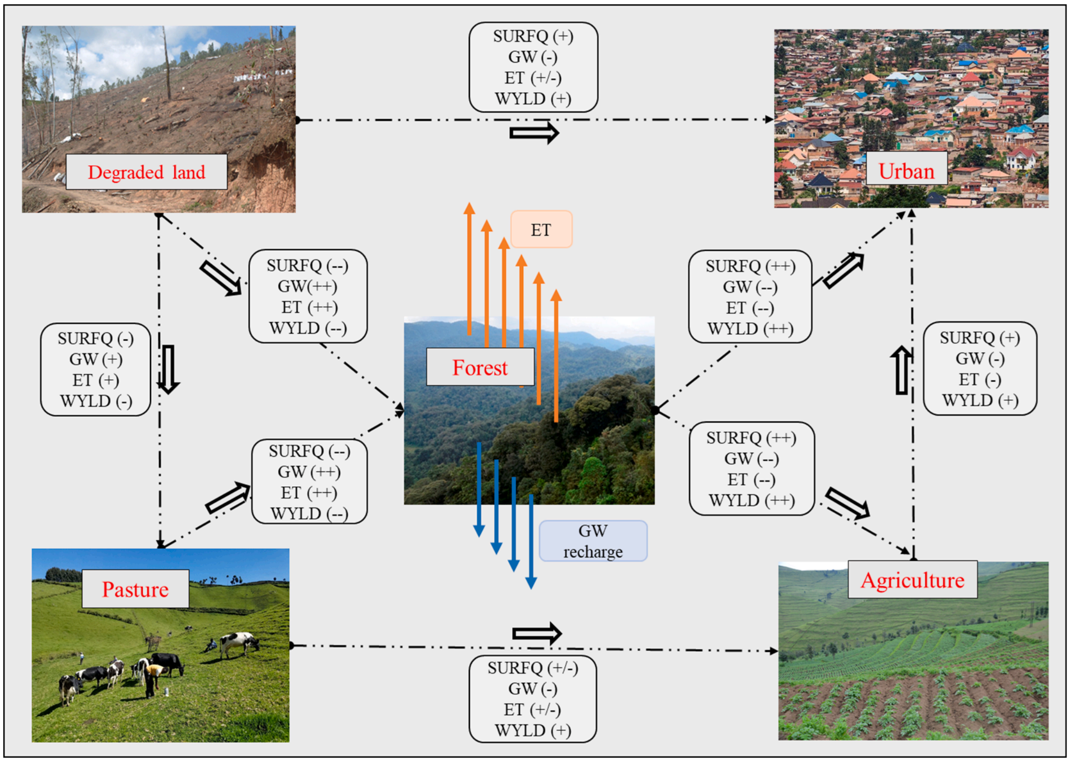

Fig. 2. A transition matrix of the changes in the water balance components due to LULCC. There are five main LULC classes (forest, agriculture, urban, pasture and degraded land), and four main hydrology components surface runoff (SURF), groundwater (GW), evapotranspiration (ET) and Water Yield (WYLD). It shows the increase/ decrease (+/-) as well as high increase/ high decrease (++/–).

dynamics in channel morphology are attributed to flow velocity, riverbank erosion, sediment deposition, and changes in riverine vegetation cover, that are induced by both human activities and climate change (Langat et al., 2019; Verma et al., 2021). Vegetation cover and hydrological regimes play an important role in the morphological processes of a river (Kijowska-Strugała et al., 2017). Consequently, the transition from natural vegetation to unvegetated landscape often decreases the surface roughness, and increases the flow velocity which causes soil erosion and sediment transport (Bekele et al., 2018). The changes in the magnitude and timing of river flows and sedimentation lead to alteration and instability of river systems (Ibitoye, 2021; Roy & Sahu, 2016). Moreover, a reduction in water yield and/ or a drop in groundwater levels and associated reduction in baseflow may alter the small perennial rivers into intermittent regime (Yifru et al., 2021) ultimatey altering channel morphology in response to flow volumes.

Human activities –such as dam construction, mining, and agriculture, affect river morphology, through altering the channel geometry, as well as the dynamics of water and sediment movement (Bhattacharya et al., 2019; Ramani et al., 2021). The same applies to upstream LULCC within catchments, which directly contribute to the changes in water and sediment movement (Wiejaczka et al., 2014; Woldesenbet et al., 2018). Prokop et al. (2020) found that long-term LULCC have accelerated water and sediment fluxes, hence, resulted in riverbank erosion, bed aggradation, and an increased risk of flooding.

Streams in **forested** landscapes tend to be hydrologically and geomorphologically more stable than in other landscapes (Roy & Sahu, 2016). They usually have wider and more stable channels with less sediments (Allan, 2004; Wubalem & Yihunie, 2021). This is in part because of the higher water retention capacity, lower discharge, reduce streamflow velocities, and lesser sediment load, as well as a stable bank slopes (Wubalem & Yihunie, 2021). Usually, forests provide effective protection from shallow landslides and soil erosion, primarily because of root binding and a lower water deficit in the soil (Vanacker et al., 2005). Therefore, deforestation accelerates runoff response such as the timing of peak flows and may result in an increased flood volumes and sediment transport (Hassaballah et al., 2017). Long-term afforestation has been accompanied with river adjustment, channels becoming more narrowed with reduced sinuosity, and secondary channels tending to be abandoned (Fernandes et al., 2020; Scorpio & Piégay, 2021).

Agricultural lands are characterized by increased surface runoff and sediment transports compared to forests (Baker & Miller, 2013). As such, streams in agricultural landscapes are characterized by sediment-laden beds and deeply incised valleys with severe bank erosion (Roy & Sahu, 2016). Additionally, transition from vegetated to uncovered lands (after crop harvest) increases the stream discharge and sediment yield (from end of growing season rainfalls), which are a major determinant of river morphology dynamics (Ibitoye, 2021; Obahoundje et al., 2018; Sinha & Eldho, 2018). A study in Lake Tana-Beles (Ethiopia) found that erosion rates on agricultural lands were much higher compared to all other land, due to the cropping on steep slopes (Woldesenbet et al., 2018), indicating the important interaction of LULC and topography.

An extension of **bare land** and **grazing land** over vegetated lands results in increased surface water and sediment flows. Thus, making stream channels wider and shallower from active channel erosion and sediment deposition (Yousefi et al., 2019). In addition, it leads to an increase in peak flows and a reduction in the time of concentration (Moraes et al., 2018). Allan et al. (1997) study revealed that sediment yields increased dramatically with agricultural expansion, less dramatically with increase in urban lands, and reduced with forest cover increase. Moreover, rivers draining agricultural lands have a higher sediment yield compared to other land cover types.

3. Material and methods

3.1. Geographical description: Areas of study

The tropics are regions between the tropic of Cancer (23 degrees North latitude), and the tropic of Capricorn (23 degrees South latitude).

They cover about 40% of the planet's land surface, within the boundaries of at least 70 countries (Racke et al., 1997). The region is home to around 40% of the world's population, which is expected to increase to over 50% by 2050 (Marcotullio et al., 2021; UN, 2010). Based on Köppen climate classification, climate in the tropics is classified into three types: 1) tropical rainforest (Af), 2) tropical monsoon (Am), and 3) tropical wet and dry savanna (Aw) or (As). The general pattern of the tropical climate is warm temperatures, with a monthly mean temperature ranging from 18 degreesC in Am to 25°C in Af. Rainfall patterns vary from Af with plenty of rain throughout the year (>2000 mm), to Am (>1000 mm) and Aw (<1000 mm) where there is a seasonal shift in rainfall patterns (Beck et al., 2018; Chen & Chen, 2013). While specific land cover types differ between different areas, forests abound in the tropical region: tropical forest covers 17 million km^2 (about 31% of ice-free land), dry forest accounts for 4%, and tropical savannah takes up 15% (Marcotullio et al., 2021).

3.2. Inventory of case studies

In this review, we synthesized peer-reviewed papers published between 2010 and 2021, focusing on the assessment of hydro-morphological responses to LULCC and CC, in the tropical regions. The literature search was carried out using the web of science database (https://www.webofscience.com). Search results were categorized into two components: 1) hydrology of tropical rivers and 2) morphology of tropical rivers. Fig. 3 outlines the filtering process used to screen the existing literature.

The first filter yielded 1,140 papers on hydrology and 149 papers on river morphology. A set of pre-defined criteria was set to screen the identified papers. These criteria are grouped under the label #1 and are as follow:

- Land use land cover change
- River hydrology (streamflow, surface runoff, groundwater, baseflow, water yield, sediment yield and evapotranspiration)
- River morphology (channel cross section, channel erosion, channel aggradation and riverbank characteristics)
- Publication time: 2010 to 2021

For articles related to river hydrology, after manually screening using criteria #1, 202 articles were identified. A second filter that considered the spatial region (tropical areas in this case) yielded 52 articles. We used the same approach for river morphology component. Ultimately, we found 20 out of 149 references on morphology after the first screening, of which 10 were within the area of interest. Two articles were identified under both components. In total, 60 peer-reviewed papers (Fig. 3) were used for our analysis, of which 30 are related to Africa, 19 for Asia, and the remaining 11 for South America (Fig. 4).

3.3. General framework of the methods applied

Geospatial data are important for understanding the way in which the earth surface changes and how its hydrological system works (Mulungu and Kashaigili, 2012). The hydrological responses to LULCC and CC have been widely analyzed with most of the studies using integrated approaches involving Geographical Information Systems (GIS), Remote Sensing, statistical analysis, and other models (e.g.: hydrological models). A combination of remote sensing data and GIS provides an efficient and affordable method for exploring changes in the earth surface (Shahrood et al., 2020; Singh et al., 2015), and river morphological dynamics (Tariq & Shu, 2020) on a spatial and temporal scale, as well as simulating the future change scenarios (Hamad et al., 2018). This is only possible because of the satellite imageries that are repetitive (Andualem et al., 2018).

For the identified case studies, Fig. 5 presents the range of application of methods used in the analyses. These methods are classified into change analysis for LULC and Climate, and the hydrological and morphological impacts assessment.

3.3.1. LULC assessment techniques

The majority of the reviewed articles used satellite images to generate LULC classification maps. Techniques for classifying images include object-based image analysis (Koneti et al., 2018), as well as pixel-based methods including supervised (Sinha & Eldho, 2018), unsupervised and hybrid (Aragaw et al., 2021). Out of 60 reviewed papers, 41 applied per-pixel classification methods, especially supervised approaches. Others used existing classified maps sourced from Government departments or global data, such as MODIS LC, GlobeLand30-NGCC, and Indian Space Research Organization (ISRO).

Thereafter, the transition matrix derived from classified LULC maps, together with socio-economic and biophysical driving factors, were used to simulate potential future LU scenarios (Teklay et al., 2021). The simulation were conducted using either land use models (Abe et al., 2018) or statistical methods and assumptions (Getachew et al., 2021). Some models apply the aspect of land demand based on the historical trend, then spatially allocate them based on the dependent variables (Das et al., 2018; Khoi et al., 2021). Three types of models are commonly used, such as empirical-statistical based on mathematical equations, spatially explicit or rule-based, and agent-based models (Han et al., 2015). A total of 12 reviewed papers used a variety of models to predict the spatial pattern of LU scenarios based on historical trends –transition based, or the simulated hypothesis –predictive based models, with CA Markov being the most used model.

3.3.2. Climate change assessment methods

In addition to LULCC, studies also considered the impact of CC on historical and future hydro-morphological changes. The meteorological time series were used for statistical trend analysis, as a basis of historical

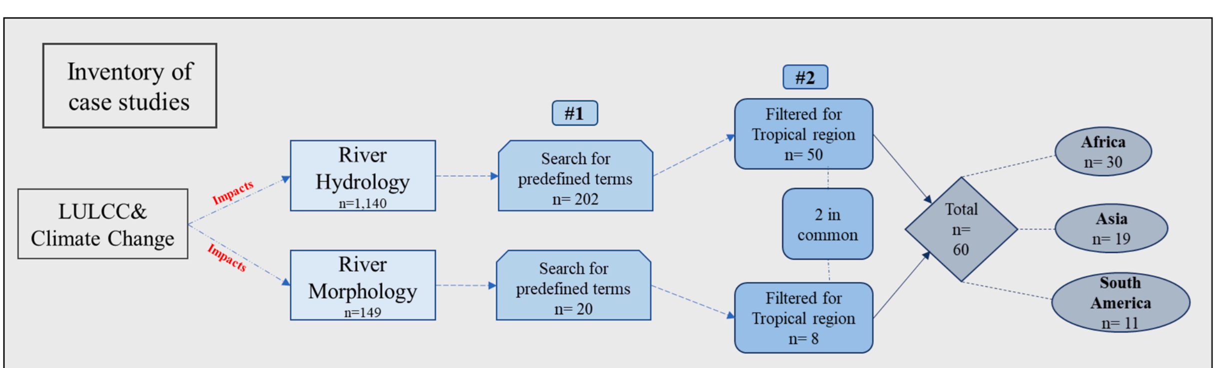

Fig. 3. Inventory of case studies.

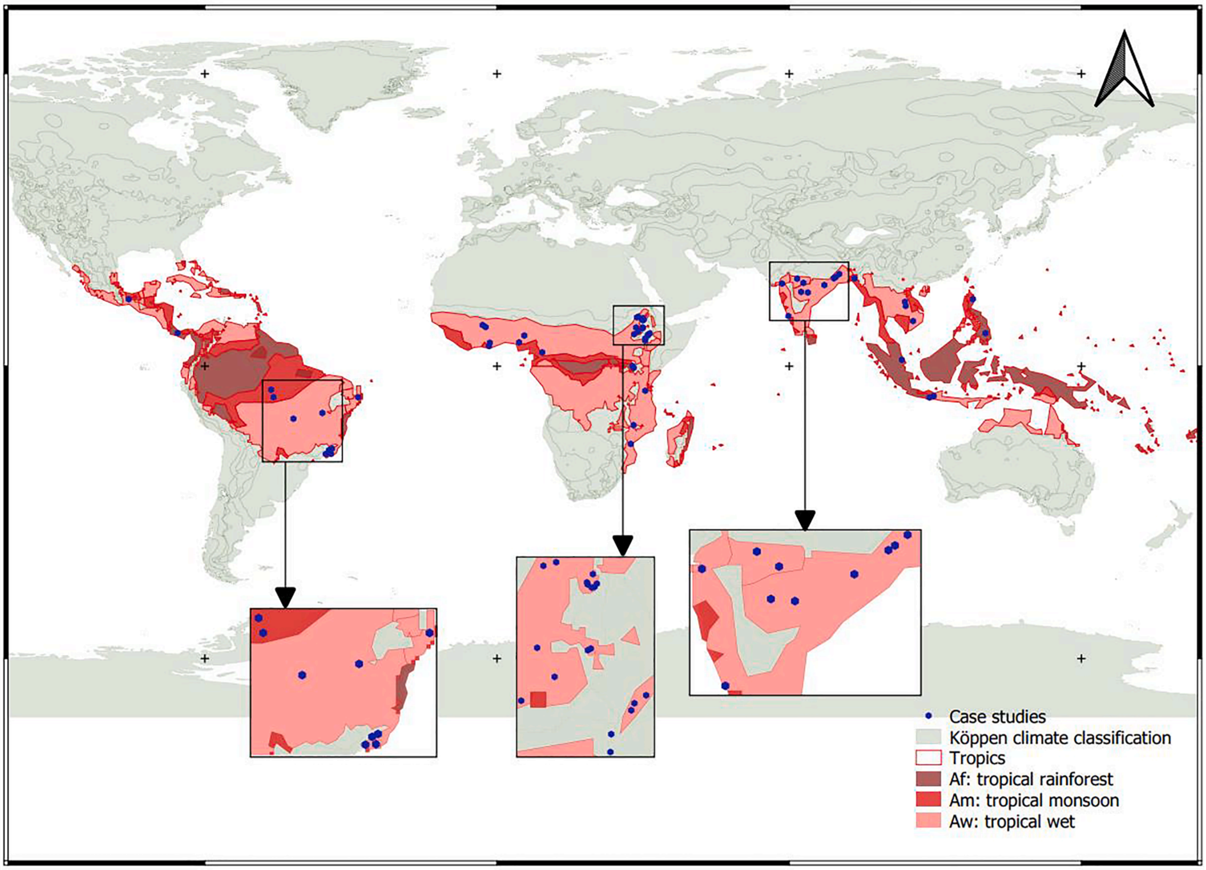

Fig. 4. Identified case studies in the tropical region.

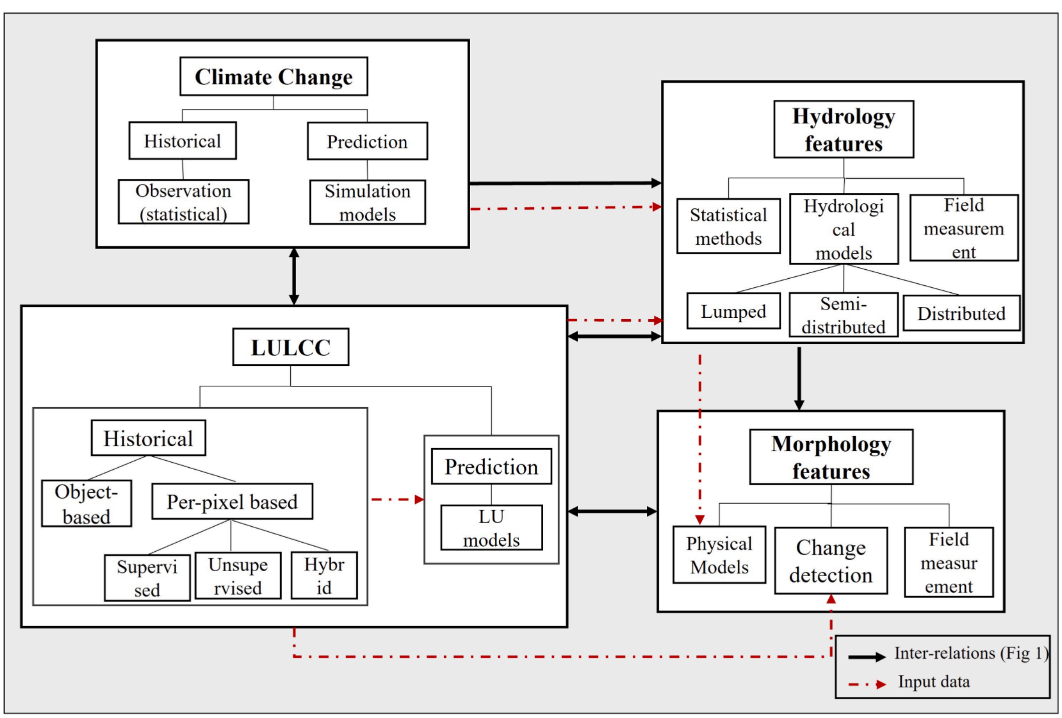

Fig. 5. Assessment approaches for the selected papers.

CC (Rientjes et al., 2011), while future CC was simulated using climate models (Sridhar et al., 2019) or based on scenario assumptions (Legesse et al., 2010).

Future CC was simulated based on the four different Representative Concentration Pathways (RCPs) defined by the IPCC (Teklay et al., 2021). Studies have been using Global Climate Models (GCMs) datasets for large scale CC data, or the Regional Climate Models (RCMs) derived from downscaled GCMs (Kumar, 2019; Pachauri et al., 2014; Yifru et al., 2021). To improve the accuracy of climate data at a small scale, studies combined several climate projection models at varying spatial resolution rather than relying on a single model (Bessah et al., 2019; Pandey et al., 2021; Sridhar et al., 2019). Other studies used the ensemble mean of multiple RCMs in their precipitation and temperature projections, to avoid substantial differences between individual RCMs (Dibaba et al., 2020).

3.3.3. Hydrology features

Most of the case studies applied an integrated approach involving GIS, Remote Sensing, statistical analysis, and hydrological models. There are two major categories of methods applied: statistical and simulation-based. Statistical methods are used to analyze historical data, whereas simulation models are used to predict future scenarios. Though there is tendency in combining both methods to analyze historical trends (Wei et al., 2013). Hydrological models can be classified into three types, namely lumped, semi-distributed, and fully distributed models (Wei et al., 2013; Zhuo et al., 2014). Lumped models describe a watershed as a single unit, whereas distributed models discretize the watershed into hydrologic response units with homogenous land characteristics (e.g. slope and soils) (Jajarmizadeh et al., 2012; Mohammed et al., 2018). Fully distributed models are generally more detailed compared to semi-distributed, with each grid-cell representing one LU type (Pina et al., 2016). The SWAT model is an example of a physically based semi-distributed hydrological model, and it has been used in about a third of the reviewed papers.

3.3.4. Morphology features

The morphological assessment includes assessing the channel forms, geomorphic adjustment, and human interventions (Belletti et al., 2015). The methods range from image classification and change detection, to field assessment and models. Satellite images are commonly used to detect changes in river morphology by identifying how the channel migrates or shifts over time (Mohamad et al., 2018; Wubalem & Yihunie, 2021). In the reviewed papers, three methods were applied, including image classification and change detection, statistical methods, and physical models, all along with field surveys. The assessed morphological features include erosion/ deposition of the banks, bank line migration, bar growth, channel bed elevations, and channel cross-sectional geometry (Langat et al., 2019; Tariq & Shu, 2020). Empirical models were used to analyze the diverse morphological elements and hydro-dynamic features of a river (Shahrood et al., 2020). Predictive models such as conceptual models based on historical trends and numerical models have been used to simulate future morphological scenarios (Surian & Ziliani, 2012). ARIMA (Autoregressive integrated moving average) is an example of autoregressive model used to predict the future river behaviors (Verma et al., 2021).

3.3.5. Uncertainties in hydrological, climate and LULC models

Climate, land use, and hydro-morphological models contain uncertainties derived from parameters and model structure (Teklay et al., 2021). This is known as equifinality, and it is one of the most prominent source of uncertainty (Naha et al., 2021). Uncertainties also arise from input data such as soil, classified LULC, and both observed and simulated climate data (Araza et al., 2021; Sinha & Eldho, 2018). Models for small catchments are often subjected to uncertainties when applied to coarse resolution data (Araza et al., 2021; Raihan et al., 2021). However, large-scale basins also represent uncertainty risks due to the difficulty of accounting for spatial heterogeneity of basin characteristics (Pandey et al., 2021). Moreover, projections are uncertain due to lack of socio-economic data, policy and regulation information related to future development, as well as in-situ data (Gomes et al., 2021; Pandey et al., 2021).

In order to minimize uncertainties, models parameters are typically calibrated, generally based on observations (Araza et al., 2021). Regarding uncertainty in climate input data, a variety of bias correction methods have been developed to reduce uncertainties from different climate models, such as the delta method for temperature and quantile mapping (QM) for precipitation (Raihan et al., 2021), or more advanced methods such as multivariate bias correction (Vrac, 2018). In addition, Monte Carlo simulations have been used, in the reviewed articles, to identify behavioral model simulations accounting for parameterization uncertainties (Naha et al., 2021).

3.4. Meta-analysis

Based on studies that investigate temporal changes, we examined the impact of spatiotemporal changes of Land Use Land Cover on river hydro-morphology. We found that 45 of 60 case studies included in this review examined LULCC and their responses over several decades (before and after comparison). As for the remaining 15 studies, some compared catchments with different LULC types (Dias et al., 2015; Ogden et al., 2013; Prokop et al., 2020), others explored general terms such as water balance (Chemura et al., 2020), infiltration rate (Olang et al., 2011), peak flow and flood (A. Horton et al., 2021; Moraes et al., 2018). Additionally, we differentiated historical (observed) and future (simulated) periods, creating 69 different datasets from 45 case studies. Supplementary material summarizes the findings from the 60 articles including CC scenarios considered for each case study.

4. Results

Table 1 illustrates the findings for LULCC (percentage change per catchment) and their hydro-morphological responses (percentage change based on the baseline), as well as their climate classifications. We considered four major LULC classes including forest, agriculture, built-up and bush/ shrub/ grass, and five hydrological components such as streamflow, surface runoff (SURQ), evapotranspiration (ET), ground water (GW), and water yield (WYLD).

Based on the results from Table 1, the major changes in the LULC are the expansion of agriculture and the decline of forest cover, with few occasions of forest expansion. According to our analysis, findings are categorized into four main outcomes.

(i) The general trend has been the natural vegetation/ forest loss, primarily associated to agricultural and/ or urban expansion, while other classes (bushes, shrubs, and grasslands) have fluctuated. Such changes resulted in an increased streamflow, surface flow and water yield, coupled with a decreased ET and groundwater recharge. For example, Gidabo River Basin (Aragaw et al., 2021), Benin Owena River Basin (Aladejana et al., 2018) and Upper Brantas River Basin (Setyorini et al., 2017).

(ii) Increase in forest land associated with a decrease in agriculture, grassland and/or shrubland, mainly the reforestation scenarios (Gomes et al., 2021; Teklay et al., 2021), resulted in decreased streamflow and surface flow while ET increased. This is consistent with past afforestation/ forest gain in Nyong River Basin (Ewane & Lee, 2020), Godavari River Basin (Hengade & Eldho, 2019).

(iii) In terms of morphology, the expansion of agricultural lands, coupled with increased water and sediment yields (Kenea et al., 2021), has contributed to riverbank erosion and channel sedimentation. Additionally, due to sediment deposition and riverbank erosion, River Niger resulted in dual centerlines and the

Table 1
Infographic representation of LULCC (%) and its hydro-morphological responses (%).

	Basin/ Reference	Country (ies)	Climate	Time period	LULC Major changes				Hydro-morphological changes					Scenario
					Forest	Agriculture	Bush, Shrub & Grass	Built-up	Stream flow	SURQ	ET	GW	WYLD	
1	Wami River Basin (Twisa, Kazumba et al. 2020)	Tanzania	Aw	2000-2016	-15,4	7,3	11,2	0,14		7	-1	-1	2	(i)
			Aw	2016-2032	-4	1,7	2,3	0,12		4	-0,2	-2	0,7	(i)
2	Upper Baro Basin (Getu Engida, Nigussie et al. 2021)	Ethiopia	Aw	1987-2017	-6,4	18	-25,2	13,5	9,5	5,6	-1,2	-10,2	0,9	(i)
3	Keleta watershed (Bekele, Alamirew et al. 2018)	Ethiopia	Aw	1985-2011	-3,2	17,8	-22,4			10,4	0,6	-3,5	1	(i)
4	Andassa watershed (Gashaw, Tulu et al. 2018)	Ethiopia	Aw	1985-2015	-1,6	14,1	-10,9	1	2,2	9,3	-0,3	-7,8	2,4	(i)
			Aw	2015-2030	-0,4	6,5	-6,1	0,9	1,7	6,3	-0,2	-5,4	1,6	(i)
5	Be River Basin (Khoi, Loi et al. 2021)	Vietnam	Aw	2005-2030	-18,9	5,4	-6,4	0,5	0,2	1,4	-0,2	-0,1	0,16	(i)
6	Upper Blue Nile River Basin (Mekonnen, Duan et al. 2018)	Ethiopia	Aw	1973-2010	-1,8	1	0,8		15,3	25,4	-10,4	-2,4	16,9	(i)
7	Muria´e River basin (Gomes, Bianchi et al. 2021)	Brazil	Aw	1986-2015	6	8	-18		17				2,4	(i)
			Aw	2015-2045 (Fossil fuel)	-4,5	11	-7			10,7	-1,9		1,5	(i)
			Aw	2015-2045 (Green roads)	15	12,5	-27			4,6	4,2		-3	(ii)
8	Upper Brantas River Basin (Setyorini, Khare et al. 2017)	Indonesia	Am	1989- 2006	-26,1	10,2	1,3	14,6	0,3	20,1	0,1	-9,7		(i)
9	Gidabo River Basin (Aragaw, Goel et al. 2021)	Ethiopia	Aw	1988- 2018	-15,6	16,7	-3,1	0,5		15,6	-1,4	-10,2	4,3	(i)
10	Benin Owena River Basin (Aladejana, Salami et al. 2018)	Nigeria	Aw	1986- 2015	-18,6	16,2	-0,3	2,8		17,3	-21,7	-22,6	18,3	(i)
11	Gumara Watershed (Teklay, Dile et al. 2021)	Ethiopia	Aw	2015-2050 (BAU)	-0,3	4,3	-4,2	0,2	0,4	5,1	-0,5	-6,5		(i)
			Aw	2015-2050 (EIC)	-9,2	9,3	-1	0	-12,5	-7,9	4,9	-19		(iii)
			Aw	2015-2050 (EFL)	39,2	-36,1	-3,1	0	-5,2	-10	8,9	1,6		(ii)
12	Netravati river basin (Sinha and Eldho 2018)	India	Aw	1972-2012	-16	11,6	-1	5,3	5,6					(i)
			Aw	2012-2030	-9,8	12,7	-5,7	2,9	2,4					(i)
13	Bilate River watershed (Sulamo, Kassa et al. 2021)	Ethiopia	Aw	1989- 2002	-9,5	5,2	-3,7	6		15	-0,3	3,9	15	(i)
14	Samin River catchment (Marhaento, Booij et al. 2017)	Indonesia	Am	1994-2013	-32	6	2	24	31		-5,3			(i)
15	Fincha'a Watershed (Dibaba, Demissie et al. 2020)	Ethiopia	Aw	2017-2036	-3,3	7,7	-4,7	1,4		6	-1,2	-1,1	1,9	(i)
				2017-2055	-4,3	8,2	-3,7	2,1		7,1	-1,4	-0,9	2,3	(i)
16	Mahanadi River basins (Das, Behera et al. 2018)	India	Aw	1985-2005	-0,5	0,3	0,1	0,2		0,03	-0,02	-0,01		(i)
			Aw	2005-2025	-0,5	0,3	0,1	0,2		0,05	-0,1	0,08		(i)
17	Meki basin (Yifru, Chung et al. 2021)	Ethiopia, Kenya& Tanzania	Aw	2000-2010	-2,6	5,1	-3,3	0,1		7	-1		8	(i)
18	Upper Narmada Basin (Pandey, Khare et al. 2021)	India	Aw	1990-2010	-7,8	7,6	0,2	0,4		7	-5	-8	4	(i)
			Aw	2010-2030	-4	4,2	-0,6	0,4		6	-4	-8	3	(i)
19	Lake Tana- Beles/ Upper Nile Blue Basin (Woldesenbet, Elagib et al. 2017)	Ethiopia	Aw	1973-2010 (Tana)	-0,1	9,9	-9,5			15	-1,2	-3,7	2,3	(i)
				1973-2010 (Beles)	-27,7	34,7	-7			51,3	-5,8	-17,4	1,6	(i)
20	Mahanadi River Basin (Naha, Rico-Ramirez et al. 2021)	India	Aw	2015- 2050	-15,6	12,6	3			4	-2			(i)
21	Dinder and Rahad Basins (Hassaballah, Mohamed et al. 2017)	Ethopia& Sudan	Aw	1972-2011 (Dinder, Rahab)	-28	33	-2		17		-10			(i)
			Aw		-21	50	-25		46		-29			(i)
22	Paraíba do Sul watershed (Andrade and Ribeiro 2019)	Brazil	Aw	1986-2015	-3,8	-2,2	7,9	0,6	2,5					(i)
23	Didessa River Basin (Chimdessa, Quraishi et al. 2020)	Ethiopia	Aw	1986-2015	-11,7	24	-14,2		4,02					(i)
24	Upper Crepori River Basin/ Tapajós River basin (Abe, Lobo et al. 2018)	Brazil	Am	1973- 2010	-3,6		2,4			0,8	-0,6	0,4		(i)
			Am	2003- 2050 BAU	-45,4		43,9			3	-2,4	-5,2		(i)
			Am	2003- 2050 GOV	-20		18,4			2,5	-2	-4		(i)
25	Johor River Basin (Tan, Ibrahim et al. 2015)	Malaysia	Af	1984- 2002	-4,7	1,1		0,4	0,1	4,8	-0,2	-9		(i)

(continued on next page)

Table 1 (*continued*)

	Basin/ Reference	Country (ies)	Climate	Time period	LULC Major changes: Forest	Agriculture	Bush, Shrub & Grass	Built-up	Hydrological changes: Streamflow	SURQ	ET	GW	WYLD	*Scenario*
26	Bonsa catchment (Aduah, Jewitt et al. 2018)	Ghana	Aw	1991-2011	-22,8	20,8		0,7	23,3					*(i)*
				2011-2030 (BAU)	-29	22,6		3,5	32,1					*(i)*
				2011-2030 (EG)	-23,9	16,8		3,8	27,9					*(i)*
				2011-2030 (EGR)	-23,8	16,8		3,7	28,1					*(i)*
27	Wamkurumadzi River, Shire Basin (Nkhoma, Ngongondo et al. 2020)	Malawi	Aw	1989-2015	-4,2	-15,49	-13,33	32,9	16,6					*(i)*
28	Fincha'a Watershed (Kenea, Adeba et al. 2021)	Ethiopia	Aw	1994-2018	-32,3	27,2	-9,7	2,9	46,7					*(i)*
29	Tapacurá River basin (Santos, Silva et al. 2015)	Brazil	Aw	1967-2008	-3	11	-8	1	3,1					*(i)*
30	Xopotó River Basin (Moraes, Santos et al. 2018)	Brazil	Aw	1989-2015	-9,9		7,9	2,3	3,4					*(i)*
31	Agusan River Basin (Santillan, Amora et al. 2019)	Philippines	Af	1995-2017	-4,9	3,2	0,7	1,5		31,4				*(i)*
32	Halda Basin (Raihan, Ondrasek et al. 2021)	Bangladesh	Am	2000-2020	-0,3	-13,2	-0,3	13,9	1,2					*(i)*
				2020-2040	-0,35	-20,7	-0,2	21,3	6					*(i)*
33	Mekong River Basin (Sridhar, Kang et al. 2019)	China,Myanmar Thailand, Laos, Cambodia& Vietnam	Aw	1992-2015	-2	3				3,9	1,9			*(i)*
34	Upper Grande River Basin (Oliveira, de Mello et al. 2018)	Brazil	Aw	2013 (20% deforestation)	-3,1				0,3	1,5	-0,1			*(i)*
				2013 (50% deforestation)	-7,9				0,6	5,6	-0,4			*(i)*
				2013 (20% reforestation)	14,1				-0,9	-4,2	0,6			*(ii)*
				2013 (50% reforestation)	35,3				-2	-7,8	1,5			*(ii)*
35	Sassandra/ Mono/ Volta Basins (Obahoundje, Diedhiou et al. 2018)	Burkina Faso, Mali, Benin, Togo, Ivory Coast & Ghana	Aw	1988-2016 (Volta)	-41	19,9	11,9	8,1	32					*(i)*
				1988-2016 (Mono)	-19,4	11,4		7,7	30					*(i)*
				1988-2016 (Sassandra)	-21,8	17,8		2,4	26					*(i)*
36	Godavari River Basin (Hengade and Eldho 2019)	India	Aw	1984-2010	16,3	-9,6	-7,3	0,9		-0,6	0,4	-1,8		*(ii)*
37	Nyong River Basin (Ewane and Lee 2020)	Cameroon	Am	1987-2014	2,3	10	-15	3	-5,1					*(ii)*
38	Lake Tana/ Upper Blue Nile River Basin (Getachew, Manjunatha et al. 2021)	Ethiopia	Aw	1985-2015	-1,6	14,1		1	2,2	9,3	-0,3	-7,8	1,3	*(i)*
				2015-2030	-0,4	6,5		0,9	1,7	5,2	-0,3	-5,4	1,6	*(i)*
39	Meki River/ Ziway-Shalla basin (Legesse, Abiye et al. 2010)	Ethiopia	Aw	2000-2020	Assumption: cultivated land between 2000 and 3000 m a.s.l. transition to forest				-11,8		2,2			*(ii)*
40	Black Volta Basin (Akpoti, Antwi et al. 2016)	Mali, Burkina Faso, Ghana& Ivory Cost	Aw	2000-2013	5,8	7,1	-21,4	8,4	3,5	27	4,6	-6	4	*(i)*
41	River Njoro watershed (Baker and Miller 2013)	Kenya	Af	1995-2003	-6,9	-11,6	16,2	0,2		9		-7	2	*(i)*
42	Gomit River (Wubalem and Yihunie 2021)	Ethiopia	Aw	1989-2020	-3	26	-27	3,4	<u>*Max changes (2002-2020)*</u> Avg river depth: -0.6m (degradation) to 0.3m (aggradation) Sinuosity index: 1.3 m					*(iii)*
43	River Niger/ Study area: Lower part (Ibitoye 2021)	Guinea, Mali, Niger, Benin & Nigeria	Aw	1990-2017	-3,5		14,5		<u>*Channel width changes (1990-2017)*</u> Sect1: -842m, Sect2: +626m Sect3: -124m, Sect4: -751m Sect5: -183m, Sect6: -33m Sect7: -326m, Sect8:-662m Waterbody: -5.2%					*(iii)*
44	Upper Tapi River basin (Ramani, Patel et al. 2021)	India	Aw	1980-2010	-9,8	13,6	-5,5	1,3	<u>*Dedtalai station (1990-1998)*</u> Channel width: +5% Channel depth: +56% W/D ratio: -9.9 Velocity: +4.2 m/s Discharge: +29,412 m3/s					*(iii)*
45	Upper Gilgel Abbay catchment (Rientjes, Haile et al. 2011)	Ethiopia	Aw	1973-2001	-34,2	34,5	-3,2		-5,3					*(iv)*

channel width increased from 2.8 to 3.5 km (Ibitoye, 2021). Similar conditions also impacted the Gomit River, leading to channel degradation and aggradation (Wubalem & Yihunie, 2021). The channel width increases due to lateral erosion, and channel depth decreases due to sedimentation (Wubalem & Yihunie, 2021).

(iv) In farmlands, the majority of rainfall is converted into streamflow. However, some studies showed a decrease in streamflow and an increase in ET, as cultivated lands have expanded on forestland (Rientjes et al., 2011; Sridhar et al., 2019). This is primarily due to high evaporation rates on irrigated lands and irrigation water use (Teklay et al., 2021).

To better understand the relations between LULCC and hydrological variables, we developed scatter plots (Fig. 6) that represent streamflow/ surface runoff and ET/ GW to forest and agriculture across the reviewed case studies. Each dot in those figures represent one case study (including scenarios), and their common behavior informs general trends. Negative correlation exists between forest cover and streamflow while ET has a positive correlation with forest cover (Fig. 6a). Expansion of agricultural land is associated with increased streamflow and negatively correlated with ET (Fig. 6b). Surface runoff decreases with forest cover gain and groundwater recharge is positively correlated with forest cover gain (Fig. 6c). Reverse trends exist with agricultural land expansion (Fig. 6d).

5. Discussion

5.1. Historical change trends

Our analysis shows that all LULC types have impacts on hydrological components. However, basin/ catchment characteristics and LULCC dynamics affect the river system processes (Dibaba et al., 2020; Vanacker et al., 2005). As represented in Fig. 6, agriculture land area is directly proportional to streamflow and surface runoff, and inversely proportional to ET and groundwater recharge, while forests have the opposite relationship (Aladejana et al., 2018; Gashaw et al., 2018; Woldesenbet et al., 2017). ET is the key element in understanding the effect of LULCC especially in tropical regions, as it constitutes a significant percentage of the precipitation over the land surface (Robertson et al., 2021), and constitutes the major water consumption, through transpiration, canopy interception and eventual evaporation, and soil evaporation (Twisa et al., 2020).

Tropical regions are largely located in developing countries where demographic and socio-economic growth are the driving forces for increased exploitation of natural resources (Ewane & Lee, 2020; Kenea et al., 2021). Changes in LULC have been attributed to rapid population growth and the resulting increase in land demands for subsistence agriculture, settlements, and the use of wood and biomass fuel (Guzha et al., 2018). We found that the most pronounced changes in LULC happened before 2000s, the period when the greatest deforestation and expansion of cultivated and built-up was reported. However, since 2000s, the trends changed, as the magnitude of forest cover loss has decreased. This is attributed to global initiatives and government measures towards afforestation and restoration programs (Bekele et al., 2018; Hassaballah et al., 2017; Raihan et al., 2021).

Some global and regional initiatives towards increasing forest cover include, AFR100 (the African Forest Landscape Restoration Initiative), the Bonn challenge targeting to bring 350 million hectares of forests under restoration (Radhika Dave et al., 2018). These initiatives, are in addition to country laws and policies aimed at conservation and reforestation efforts (Andrade & Ribeiro, 2019). Brazil's Xopotó River Basin experienced an increase in forest cover due to the New Forest Code (Moraes et al., 2018). There has been an increase in forest cover in Godavari River Basin, as a result of India's effort to protect and restore natural and plantation resorts (Hengade & Eldho, 2019; Koneti et al., 2018). In addition, different countries adopted environmental friendly agriculture methods, such as soil and water conservation measures through different projects such as the National Sustainable Land Management (Mekonnen et al., 2018). The forest cover increase trend is evident from several studies (Table 1), including the forest loss (-5.2 %) in the Upper Blue Nile River Basin in Ethiopia (1973 to 1995), followed by the 3.4 % increase afterwards. Such changes were attributed to the afforestation and soil and water conservation programs that the Government initiated (Mekonnen et al., 2018). A synthesis of impacts of forest cover increase in the Andes indicate that afforestation reduced water erosion, risk of moderate floods, increasing soil infiltration rate, soil water storage and reduced (Bonnesoeur et al., 2019).

Natural and human activities such as mining, and construction of reservoirs induce riverine land cover changes. These changes lead to accelerated sediment transport and riverbank erosion, triggering thalweg shifting, channel incision and gradual change in the river cross-sections (Bhattacharya et al., 2019; Ramani et al., 2021). Tropical rivers are more prone to morphology changes as a result of increased sediments in their channels, due to uncontrolled practices such as illegal mining operations, deforestation, land tillage and overgrazing, coupled with higher precipitation leading to frequent flooding (Tanaka et al., 2021). The findings indicated that cropland, bare soil, and urban areas contribute significantly to soil erosion and sediment transport, compared to forest (Sinha & Eldho, 2018). Morphological assessment in Darjeeling Himalayas revealed that forested catchments tend to have deep and narrow channels, while agricultural channel streams were shallow, wide, and braided due to large sediment depositions in streams in agricultural lands (Prokop et al., 2020).

5.2 Future scenarios of river hydro-morphological responses to LULCC and CC

Land use and climate projections offer insights into likely future impacts (Gomes et al., 2021). Among the 60 case studies, 12 studied the impacts of future LULC and climate on basin hydro-morphology, by using scenario-based prediction. The simulations revealed similar change trends on hydro-morphological variables.

Future predicted LULCC are not as significant as has been in the past, and therefore their hydrological responses are patterned differently according to the different LU scenarios. Future LU scenarios include Business-as-usual (BAU), economic growth (EG) only, and economic growth and reforestation (EGR) models considering the implementation of government measures for afforestation/ reforestation (Abe et al., 2018; Aduah et al., 2018), expansion of irrigation crop (EIC), expansion of forestland (EFL) (Teklay et al., 2021), the green roads development and fossil fuel, based on strong and low implementation of environmental protection government directives, respectively (Gomes et al., 2021; Oliveira et al., 2018). The BAU and fossil fuel scenarios will lead to the most drastic changes (negative impacts) in terms of forest loss and economic expansion, resulting in an increased streamflow and decreased ET, increased frequency of floods, in contrast to the afforestation and green roads scenarios, thus, showing the influence of vegetation cover on water flow dynamics, quantities and occurrence of extreme hydrological events (Abe et al., 2018). EG is also expected to cause an increase in surface runoff and total water yield, followed by a decline in ET and GW recharge (Khoi et al., 2021). The expansion of forest cover scenario showed a potential decrease in surface runoff, river streamflow, and water yields, favoring water infiltration, ground recharge and soil erosion control (Farinosi et al., 2019).

Human activities will continue to impact river morphology, along with riverine land cover dynamics like sand mining and channel deviations for irrigation purposes. Riverbank erosion and sediment deposition have been found to be the major cause for the future river migration, and riparian vegetation cover increase has been proposed as a means of control (Verma et al., 2021). The results revealed that increasing cultivated land will cause severe threats on the future river hydro-morphology if no proper measures are taken (Twisa et al., 2020). Soil erosion in Mekong River Basin (China) is predicted to increase by more than half in 2040 under RCP 8.5. Both CC and LULCC will affect Mekong River Basin due to the conversion of forest to agricultural and urban areas with erosion in the central part predicted to decrease over time (Chuenchum et al., 2020).

The combined impact of CC and LULCC is predicted to have a more significant impact on basin hydro-morphology. CC is predicted to change weather patterns (rainfall and temperature) differently in different regions, affecting all hydrological components (Raihan et al., 2021; Yifru et al., 2021). According to IPCC-AR6 (2021), human-induced climate change is projected to increase in the future, resulting in more frequent droughts in some places and greater flood hazards in others, due to global warming and an alteration in precipitation patterns, respectively. The annual streamflow is expected to increase by 10–40% in the wet-tropical zones and decrease by 10–30% in the dry-tropical zones by mid-century (IPCC, 2007).

5.3. Correlations between LULCC and hydrologic variables

The trends in LULCC (forest and agriculture) and hydrological components (streamflow, surface runoff vs ET, and groundwater) are similar across several studies reviewed. In spite of this, our review reveals that LULCC impacts are highly scale-dependent, and depend on several factors, including the catchment characteristics, as evidenced by low correlations in Fig. 6. Wang et al. (2011) have reported similar findings in Northern China. Wei et al. (2003) attributed the inconsistent findings to potential masking effects of catchment size, biases and errors from different measurement methods and heterogeneity in catchment characteristics (Näschen et al., 2019).

There is still limited research on thresholds or tipping points for LULCC and hydrological indicator alterations. Findings by Tarigan et al. (2018) suggest that a watershed should contain >30% forest cover and a maximum of 40% plantation cover for maintaining sustainable waterflow regulation ecosystem services. However, the weak correlations between forest cover loss and stream flow show the potential masking effects with increased catchment area. As outlined by (Hess et al., 2010; King et al., 2014; O'Connell et al., 2007; Robinson, 1990; Viglione et al., 2016) in (Rogger et al., 2017), the impacts of LULCC on flow characteristics (including the magnitudes) become more difficult to isolate with increased catchment scale and non-homogeneity patterns such as soil type and flow aggregation. Similar masking effects are likely to result from precipitation variability within a catchment. Therefore, there is a need to undertake further research at finer scales (catchment area), in order to capture individual catchment hydrological behavior to inform decision-making in land use and water resources management.

5.4. Contrasting effects of CC or LULCC on hydro-morphological changes

There is often a discussion about whether CC or LULCC has the most influence on river hydro-morphological changes. From 60 reviewed articles, 26 analyzed the isolated and combined impacts of these changes. Three hypotheses were formulated based for the analyses: 1) CC impacts are greater than LULCC, 2) Both changes are equally significant, and 3) LULCC impacts are greater than CC.

In the first hypothesis, CC has greater impacts on hydrological components, than LULCC (Gomes et al., 2021; Tan et al., 2015). The main reason is the fact that runoff volume and ET depends heavily on rainfall and temperature, respectively (Pandey et al., 2021). Half of the cases studies revealed that changes in hydrological components are mostly explained by CC patterns, such as increased/ decreased rainfall intensity and change in temperature (Raihan et al., 2021; Yifru et al., 2021). Findings indicate that CC is expected to worsen in the future situation (Raihan et al., 2021), even though the CC simulations show high uncertainties (Näschen et al., 2019).

The second hypothesis contends that both changes impact hydrological components at a similar level (Araza et al., 2021), with LULCC being more prominent in the past and CC more prevalent in the future

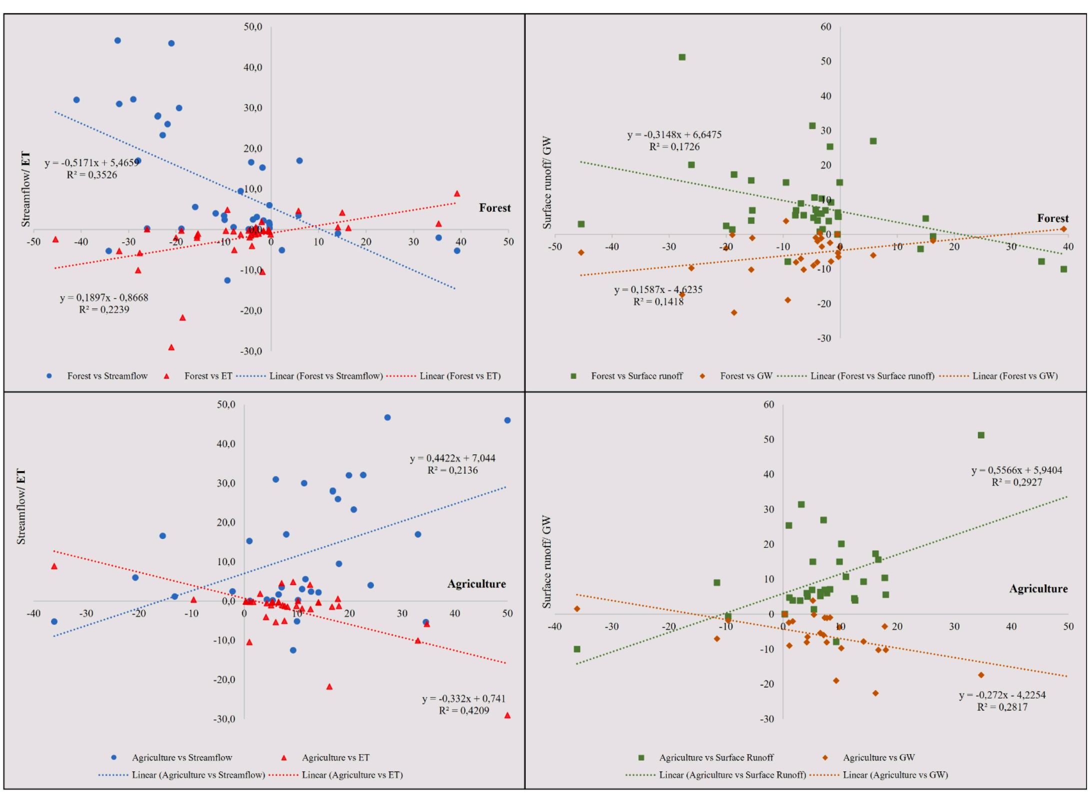

Fig. 6. Representation of changes in LULC and hydrological responses (a) Forest vs streamflow/ET, (b) Agriculture vs streamflow/ET, (c) Forest vs Surface runoff/ GW, and (d) Forest vs Surface runoff/GW.

(Naha et al., 2021). In support of this hypothesis, only five studies have been cited (Araza et al., 2021; Bessah et al., 2019; Chimdessa et al., 2019; Naha et al., 2021; Pandey et al., 2021). Whereby changes in hydrological components resulted from LULCC coupled with less CC in the past; however, according to simulations, the trend is expected to be the opposite in the future. This hypothesis highlight that changes in LULCC resulted in an increase in less permeable land and decline in vegetative lands, leading to more surface runoff and less ET (Pandey et al., 2021). Moreover, runoff and ET are expected to change due to CC in the future, and LULCC will be less significant compared to the past trends (Bessah et al., 2019).

Lastly, 8 out of 26 case studies supported the fact that LULCC impacts are more significant than CC (Chemura et al., 2020; Obahoundje et al., 2018). This is attributed to the relative minor changes in climate, and/ or substantial LULCC during the study period (Birhanu et al., 2019; Marhaento et al., 2017). Scale appears to play a significant role, as changes are more noticeable in small catchment than large basins (Aragaw et al., 2021). In relation to morphology, results from 4 out 10 cases studies demonstrated that human-induced activities (dam construction, and mining) have a greater impact on sediment production, soil erosion, and riverine vegetation dynamics, more than CC (Ahmed & Fawzi, 2011; Setyorini et al., 2017; Song et al., 2016).

According to the reviewed articles, the dynamics of river hydromorphology are controlled by two factors: rainfall and temperature input, and the processes influenced by the input and the basin characteristics. Therefore, CC governs the input, and the LULCC describes the basin characteristics. This implies that both LULCC and CC affect river flow regimes and extreme events in an intertwined way (Kumar et al., 2022; Nkhoma et al., 2020), whereby the magnitude and extent of changes are influenced both by basin characteristics and climate dynamics based on the extent of each change and their interaction. Furthermore, LULCC impacts CC by changing energy balances, water, and greenhouse gases from the land to the atmosphere, while climate variables also affects LULC (Sleeter et al., 2013; Tan et al., 2022).

6. Conclusion

Tropical regions have experienced the fastest LULCC in the last decades. Coupled with CC, this has affected the hydrological and geomorphological processes of river systems. The main objective of this paper is to review the impacts of changes in LULC and climate on tropical river basins, in terms of hydrology and morphology components. From our analysis based on 60 case studies, several conclusions can be drawn.

LULCC and CC lead to diverse changes in hydro-morphological properties with extent of impact strongly influenced by the scale/ magnitude of change/ driver. CC affects the river basin hydrology in terms of rainfall amounts and temperature, while LULCC enhances or decreases its impacts by defining the water conveyance. Moreover, CC and LULCC are interrelated factors that affect extreme events such as droughts and floods. Furthermore, CC impacts LULCC and vice versa, and their interactions are nonlinear.

The main trend of LULCC has been an increase in cultivated and urban land, and a decline in forest land. Along with CC, these changes resulted in an increased streamflow, surface flow, and total water and sediment yields (erosion rates), and a decrease in ET and groundwater recharge. The future is expected to follow the same trend, with variations based on implementation of conservation measures including reversing forest cover losses and optimization of development trajectories with due consideration of land cover. The changing hydrology combined with human-induced activities such as mining, reservoir construction and riverine vegetation changes, have led to increased riverbank erosion, channel migration, and changed rivers cross-sections. The relatively low correlation between LULCC and hydrological variables indicates that other catchment characteristics such as soil, climate, or topography, also play an important role.

A number of the case studies analyzed in this review use models (land use change, hydrological, climate change). It is crucial to consider uncertainties from model parameterization and structure in the change impact assessment and include the uncertainty analyses in model outputs to ensure more robust and reliable results. Since most studies used in this review analyzed impacts of forest transition to other LU types, more research is needed on other LULC transitions to better comprehend the wide-ranging effects of LULCC on river hydro-morphology. The majority of the reviewed papers (37 out of 60 papers) are from three countries (Ethiopia, India, and Brazil), therefore, more studies in other parts of the tropical region are required to improve our understanding of river morphology, land, and water resource management in light of future changes. Research should focus on the combined impacts of CC and LULCC, given the intricate nature of these drivers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.128702.

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