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RESEARCH

Land use, land cover changes and expansion of artificial reservoirs in Eastern Thailand: implications for agriculture and vegetation drought reduction

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Abstract Eastern Thailand and Rayong province face perennial drought and water scarcity due to natural characteristics of climate and geology. Therefore, increasing water surface by man-made reservoirs is one of the priorities in the regional development plan to provide water adequately for industrial purposes, domestic consumption, and agriculture. The large reservoir constructions may induce land use, land cover changes (LULCC), yet it also is expected to alleviate the drought harshness in the region. By delineating Landsat satellite images and spatial analysis, this study revealed the LULCC in Rayong from 1990 to 2020. The most prominent LULCC was surface water expansion, about 10.9% per year, yet the increase was the most substantial in the first decade rather than the last two decades. Vegetation expansion was observed, contributing to an increase in forests/plantations and intensified agriculture by 39.19% and 25.54%, respectively. The LULCC corresponded to a 3.64% increase in ecosystem service values (ESV), implying positive benefits from the LULCC. Vegetation drought conditions monitored by the vegetation health index (VHI) exhibited an improvement trend, especially in the eastern basins. The development of artificial reservoirs was proven to stimulate the expansion of intensive agriculture and vegetation drought mitigation with spatial heterogeneity, spreading mainly across areas of the basins rather than remote areas. The research findings inform the efficiency of the reservoirs and irrigation systems regarding the beneficial effects on drought mitigation and water scarcity for agricultural cultivation. They also provide spatial information on areas still hindered by water problems that should be addressed in future strategies.

Keywords Ecosystem services · Surface water expansion · Man-made reservoirs · Land use · Land cover changes (LULCC) · Vegetation drought conditions

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Introduction

Fresh surface water is an essential part of terrestrial ecosystems that sustains life on Earth. Although the planet appears awash in water from space with about 71% of the Earth's surface, only 3% of this water is fresh. The forms of glaciers and ice caps lock most of the freshwater away, leaving only 0.3% readily available for use as surface water in the forms of lakes, rivers, streams, and inland wetlands (Musie & Gonfa, 2023). Despite its limited volume, surface water substantially contributes to shaping ecosystems and driving human life (Gopal, 2020). The population explosion puts immense pressure on existing water resources (Cosgrove & Loucks, 2015). Economic development with diverse industrial production and agriculture requires high water demand, leading to a sharp increase in water consumption from the 1950s. More explicitly, agriculture and freshwater have an inextricable relationship, which engages approximately 70% of global shared water consumption for agricultural production (Lawan & Surendran, 2021). Climate change will exacerbate this challenge by shifting precipitation and hydrological patterns, increasing evaporation rates, and increasing the frequency and intensity of extreme flood and drought events (Cosgrove & Loucks, 2015; Jackson et al., 2001).

Thailand is one of the top freshwater users in its supply chain regarding water scarcity (B. Chen et al., 2018). Eastern Thailand is a typical region, which frequently faces water shortages for production and domestic uses. It is caused by the natural characteristics of climate, terrain, and geology. More specifically, Eastern Thailand is mainly characterized by mountains and short hills alternating with low plains. A chain of the eastern mountains blocks the southwest monsoon winds; therefore, the western parts of the region (i.e., Rayong and Chonburi provinces) get lower rainfall than the eastern areas (Nguyen et al., 2023). The geological characteristics of this region are mainly contributed by sandy soils with major hydrogeological units of meta-sediments, colluvial deposits, and granites leading to low groundwater resources (Seeboonruang, 2016). This region frequently encounters severe drought and water deficit, which have posed threats to local water supply and crop productivity (Promping & Tingsanchali, 2021; Tanguy et al., 2023). The situation is predicted to worsen in the future due to climate change (Seeboonruang, 2016). For example, Rayong faced extreme water shortages in 2005 that required water mobilization from other provinces to address this problem (Phadungsontikul, 2022; Pink, 2016). Recurring drought and water shortages induce critical economic losses, especially in the agricultural sectors, and pose a critical challenge with far-reaching impacts on the economy and ecosystems (Ikeda & Palakhamarn, 2020; Yoshida et al., 2019). Severity of the increasing drought in Rayong underscores the need for immediate and effective actions to solve this problem. Therefore, the development of surface water in this area by artificial reservoirs to support regional economic activities is the top priority along with the Eastern Economic Corridor (EEC) plan—the special economic strategy to revive the national economy (Boonyanam & Bejranonda, 2022; Nguyen et al., 2021).

Most ecosystems and traditional agricultural systems (e.g., rainfed rice) rely on rainfall and natural rivers/canals as the primary water sources for cultivation and domestic use. Yet, this manner is inherently vulnerable to variations in precipitation patterns (Hayashi et al., 2018; Sathyan et al., 2018). For example, it may be redundant in the rainy season causing floods, while water shortages may frequently occur during the dry season leading to crop failures (Bodner et al., 2015; Diem et al., 2024; Klock & Sjah, 2011). Man-made reservoirs are often a part of greater water supply and irrigation systems, which play a critical role in terrestrial water systems. By altering natural water fluxes and water storage, the reservoirs potentially mitigate drought and water shortage through water management and reasonable regulation (T. Zhou et al., 2016). Moreover, large reservoirs and lakes facilitate to creation of habitats for freshwater ecosystems and wetlands, contributing to biodiversity and ecosystem functions (Y. Zhou et al., 2022). It also provides recreational landscapes and creates livelihoods for indigenous communities through tourism and fishing (Bolding et al., 2004). Yet, the construction of reservoirs also poses potential risks, such as cultivation land loss, livelihood conversion, displacement of the local population in the inundation basins, and disturbance of indigenous ecosystems in these areas (Połomski & Wiatkowski, 2023; Xin & Wang, 2021). Land use, land cover changes (LULCC) are the most prominent impacts induced by the construction of reservoirs in both headwaters and downstream areas (Antwi-Agyei et al., 2019). The LULCC in catchments and basins of reservoirs has been reported in current studies. They mostly show the negative trend of ecosystem degradation. For example, rapid urbanization along with deforestation and expansion of bare soil was found in the catchment of Owabi and Gorges reservoirs (Antwi-Agyei et al., 2019; J. Zhang et al., 2009). However, other catchments indicated the opposite trend of urban expansion, reforestation, and agricultural intensification (Bonansea et al., 2021; Eekhout et al., 2020; Huang et al., 2019). Ecosystem services in the reservoirs are also disparate depending on their state of land use and land cover (LULC). A degradation trend of LULC can lead to a low ecological environment, while an increase in natural vegetation in the basin can have positive impacts on their abundant services (Bonansea et al., 2021; Eekhout et al., 2020). Evaluation of ecosystem services is a common approach adopted to simply quantify ecological assets and rapidly provide total monetary values whenever LULCC happens instead of specific quantification each service, which is relatively complicated and requires high specialization (Costanza et al., 2014; Pham & Lin, 2023).

Monitoring of artificial reservoirs includes water volume and surface expansion. The first metric indicates the amount of water availability, while the later further emphasizes the impact related to LULC changes due to surface water expansion. Remote sensing effectively facilitates reservoirs and surface water monitoring using different approaches (Arvor et al., 2018; W. Zhang et al., 2019; Y. Zhou et al., 2022). At the same time, satellite imagery also allows us to monitor vegetation growth and other environmental aspects such as moisture, thermal condition, and dryness (Pei et al., 2018; Shan et al., 2019; West et al., 2019). It is therefore able to combine these conditions for environmental monitoring and assessment as well as drought conditions.

The reservoir projects are initially aimed to mitigate drought and benefit local environments. Therefore, this research aimed to combine the abilities of remote sensing to comprehensively investigate problem, which includes the dynamics of LULCC in Rayong province, an eastern province of Thailand with several issues of drought and water deficit, along with surface water changes over the past three decades from 1990 to 2020. It discovered the principal LULCC trend along with total ecosystem service changes caused by LULCC. The drought conditions were also observed by vegetation drought response, represented by vegetation health index (VHI). Simultaneously, it was assumed that an increase in water surface is associated with drought alleviation and agricultural expansion. It should be noted that ecological environments are not uniform because they are significantly different between regions due to terrain constraints and local conditions (e.g., economic, population, and policy). The effect of reservoirs on agriculture and drought mitigation may be weakened by negative effects in extensive urban areas, terrain characteristics, and local effects of reservoirs. Therefore, this hypothesis was examined by a local regression model of geographically weighted regression (GWR), a widely used method to evaluate controlling factors in environmental studies, to minimize local impacts (Brown et al., 2012; Deilami et al., 2018; Nguyen et al., 2023). This work is expected to contribute to the current knowledge pool related to the economic and ecological benefits of freshwater conservation. It also assists local stakeholders in delineating the efficiency of irrigation projects in drought alleviation and hindered regions for better water supply.

Materials and methods

Study area

This study's area of interest is Rayong province, located in eastern Thailand (Fig. 1). It is a coastal area with an east–west coastline about 90 km long. The topography is characterized by a mixed terrain with an average elevation of 73 m. The low-flat plains are distributed along the coast at two major basins of the Rayong (RYB) and Prasae rivers (PSB) (Tongnunui & Beamish, 2009). They are interspersed with short hills and mountains (~ 1200 m) that divide the terrain in a clear north–south direction (Phan & Manomaiphiboon, 2012). According to the Thailand Land Development Department (LDD), the majority of this area is covered by sandy loam soil mixed with limited water-holding capacity (Nguyen et al., 2023). Also, rivers are relatively short and narrow, so natural surface water resources are not too abundant.

Although the climate varies slightly by province and is even deemed unpredictable due to climate impacts, Rayong has a climate compatible with that

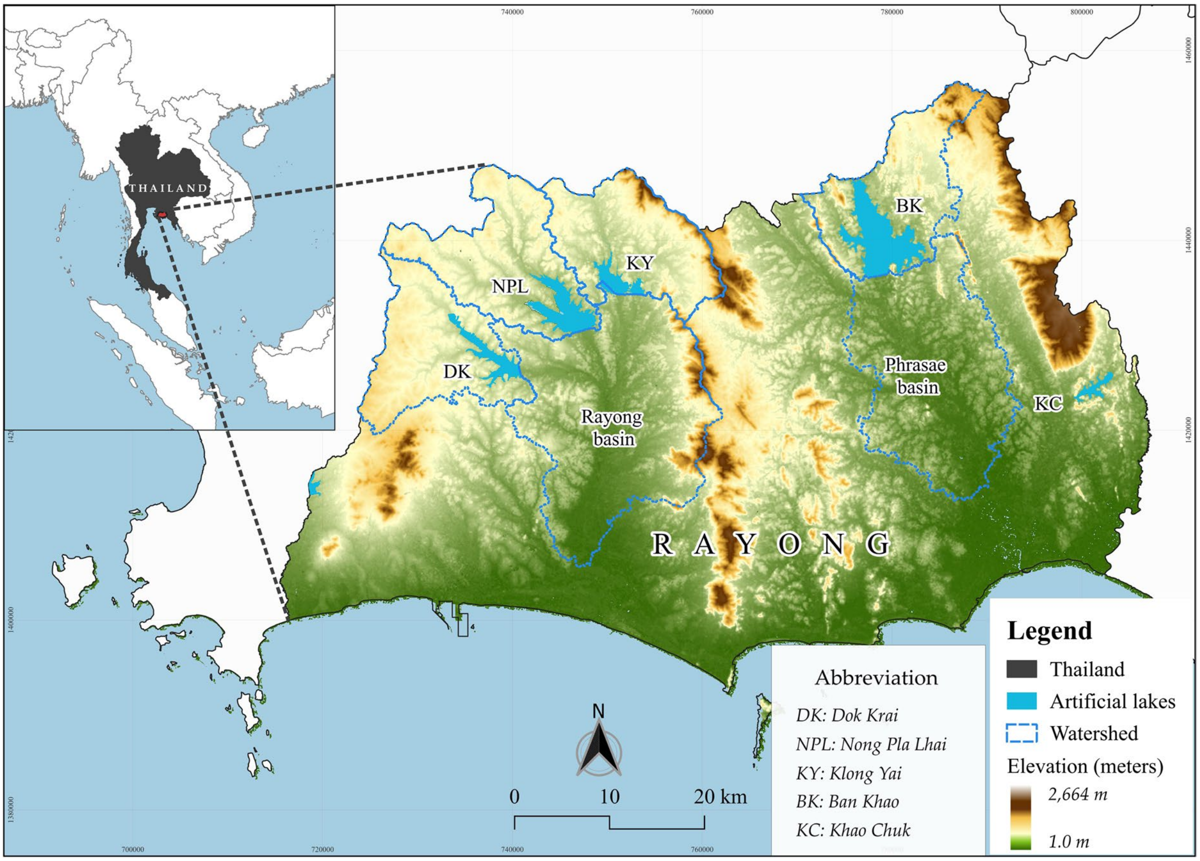

Fig. 1 Map of Rayong province depicts its location in eastern Thailand, terrain characteristics, current artificial reservoirs, and watersheds

of the eastern region (G. Chen et al., 2024). The provincial average rainfall is comparatively low compared to that of Thailand, around 1500 mm/year (Sumdang et al., 2023). The two prevailing monsoons are the southwesterly and northeasterly, which form the wet season (May–October) and the dry season (November–April). The topographic and climatic characteristics render this region particularly prone to drought and water scarcity during the dry season (Samanmit et al., 2022).

Moreover, Rayong is also one of the provinces in the Eastern Economic Corridor (EEC), which is planned to revive the country's economy. This is the highest gross domestic production (GDP) province in Thailand with intensive industrial activities. It is also a significant agricultural area, balancing new industrial activities and previous agricultural production. In spite of owning limited water resources, indigenous cultivation is still based on agricultural production, with over 50% of paddy fields, perennials, and orchards, e.g., oil palm, coconut, durian, longan, manosteen, pineapple, sugarcane, and cassava, that require high water demand and water footprints in production (Boonkaewwan et al., 2021; Gheewala et al., 2014; Jampanil et al., 2012; Phadungsontikul, 2022; Samitthiwetcharong et al., 2023). The province has been undergoing rapid and dynamic development, thus requiring large water resources for both industrial production and agricultural cultivation. The Royal Irrigation Project has been implemented with five reservoirs and pipeline linkage to distribute water and release water stress in remote areas (Jampanil et al., 2011; Nguyen et al., 2023; Vannametee et al., 2022). It should be noted that this study only considered the mainland region because the islands are not affected by surface water and irrigation projects.

Landsat satellite images

Land use, land cover (LULC), and vegetation drought conditions were monitored by different generations of Landsat images, providing consistent spectral and spatial information. Level 2 surface reflectance data was synthesized for four periods in 1990, 2000, 2010, and 2020 to cover a sufficient period for long-term assessments of reservoir projects that are typically implemented over years rather than a short period. As a coastal area, it is frequently influenced by high cloud cover that affects image quality during the rainy season. This research applied a data selection strategy to acquire high-quality images for image delineation. Specifically, all images with a cloud ratio of less than 50% captured during the dry season (January–May) in the target year and its two adjacent years were included in the initial preprocessing steps. This filter returned a set of single high-quality scenes for further analysis, i.e., 19 scenes (1990), 20 scenes (2000), 20 scenes (2010), and 38 scenes (2020). We leveraged the capacity of Google Earth Engine to preprocess these images by applying a set of the above filters, masking out cloud and cloud shadow pixels based on quality band (QA), and generating a single composite image for each target year by the median operator. Digital numbers (DN) of each band were also transformed back to reflectance values before they were utilized for LULC classification and thermal estimation. Landsat-5 (TM) was used for the periods before 2013, while Landsat-8 (OLI/TIRS) was the main data source to monitor LULC and environments after 2013. Optical spectral and thermal infrared bands were included in the analyses within this study. Figure 2 describes the workflow that Landsat images were processed, as well as key analysis components and corresponding methods to obtain secondary data and results.

Analyzing land use, land cover changes

LULC maps were delineated by applying a random forest classifier (RF) on spectral bands based on the ground truth polygons that were selected from the sampling selection framework proposed by Nguyen et al. (2022) and image visualization on Google Earth. Reference polygons were randomly digitized across the study area to delineate large and uniform regions reflecting each LULC type. Total area of reference data was allocated based on relative area of each

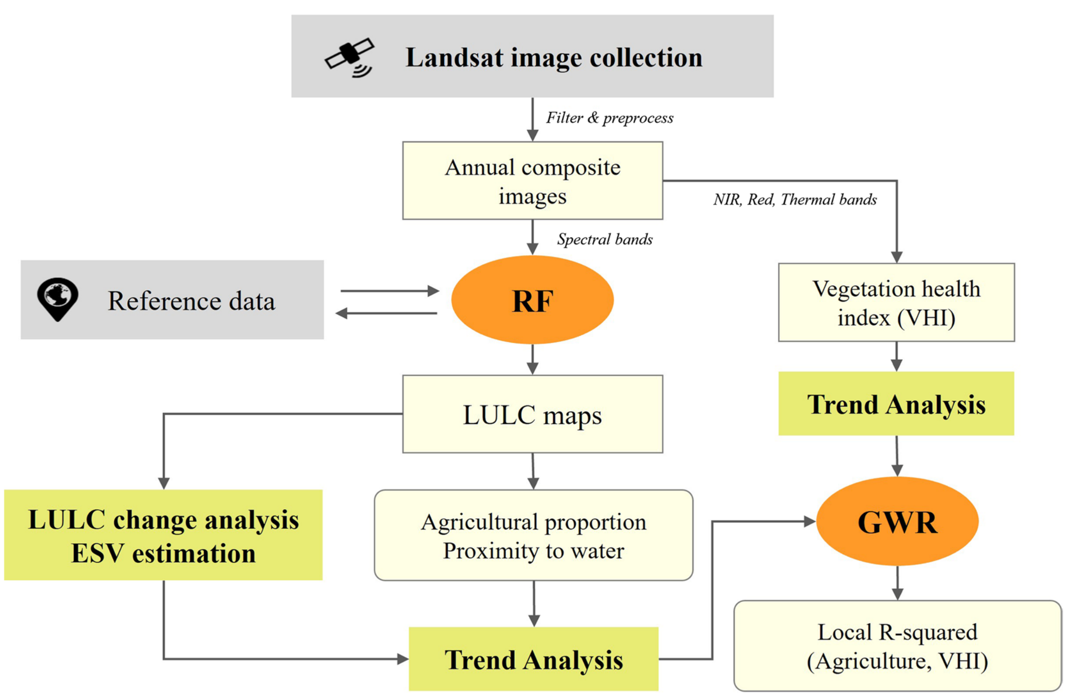

Fig. 2 General workflow describes datasets and key analysis procedures

LULC type (Supplementary Table S1). This reference data was then divided into two collections for training and validation in a 70/30 percentage ratio. The principal parameters in the RF classifier are the number of variables for each split (*mtry*) and the number of trees (*ntree*). The *mtry* parameter is automatically tuned by the random search for an optimal value using an out-of-bag error estimate. Meanwhile, the *ntree* parameter was selected based on the literature, reflecting a big enough number to ensure the chance that all predictors could be incorporated into the classification (*ntree* = *500*). The trained models were then adopted to delineate optical bands into the land use, land cover maps, including six LULC types, i.e., built-up (BUP), coastal wetland (WET), forest/plantation (including perennial, cash crops, and orchards, FOR), inland water (WAT), intensive arable land (AGR), and rainfed arable land (ARA)—mostly characterized by bare soil during the idle period (Can et al., 2021). The classified LULC maps were verified by comparing them with the corresponding validation dataset to construct confusion matrices. Subsequently, these matrices were used to derive an evaluation parameter of kappa coefficient, which has to be higher than 0.75 for a realiable result. The LULC maps achieved a comparatively high agreement level with Kappa coefficients of 0.993 (1990), 0.986 (2000), 0.991 (2010), and 0.983 (2020) (Supplementary Table S2).

LULC area and proportion in each period were estimated at the provincial base and visualized by the Sankey plot to depict LULC changes (LULCC) and transformations between the periods.

Ecosystem service valuation

Ecosystem service valuation using the benefits transfer method is a widely applied approach to quantifying landscape into economic values for peer comparison. The LULC classes in this study were collated with biomes to figure out the corresponding ecosystem service value (ESV) coefficients on Costanza et al. (2014). The ESV of urban features in this original study particularly represents urban parks with higher benefits. Applying this ESV for wide scales on residential vegetation coverage leads to overestimation. We therefore estimated dense urban areas using an alternative coefficient (2091 USD/ha/year in 2020) (Pham & Lin, 2023). There are two types of arable lands in the study area, rainfed and intensive croplands. The rainfed cropland is mainly cultivated using rainwater during the rainy season, while it is turned into idle barren during the dry season. In contrast, intensive crops are often double or triple-crops, which provide higher values because of rotational crops, e.g., food, materials, and pollination. Applying the coefficient of cropland for rainfed arable land may cause overestimation. However, it does not completely fit the bare soil (desert) and grassland biomes, and it may be underestimated. Therefore, we combined the coefficients of cropland and rangeland to estimate the rainfed arable land in this case as an average value, which reflects both cropland cultivation and grassland in rainy and dry seasons, respectively. The original coefficients were expressed in terms of 2007 USD/ha/year. They were then adjusted to the 2020 USD/ha/year using the Consumer Price Index (CPI) inflation calculator (Table 1).

The general ESV was estimated by the equations below for the entire landscape (Eq. 1). This study also calculated ESV for each grid cell for spatial analyses (Eq. 2).

$$ESV = \sum (A_k \times VC_k) \quad (1)$$

Table 1 Modified ecosystem service coefficients for corresponding LULC classes in 2020

LULC	Biome	Modified ESV coefficients (2020 USD/ha/year)
Built-up area (BUP)	High-density urban areas	2091
Coastal wetland (WET)	Swamps, floodplains	32,729
Forest, plantation (FOR)	Tropical forest	6859
Inland water (WAT)	Lakes, rivers	15,946
Intensive arable land (AGR)	Cropland	7095
Rainfed arable land (ARA)	Mixed cropland and rangeland	6203

$$ESV_i = \sum (A_{ik} \times VC_k) \quad (2)$$

where ESV is the total ecosystem services, A_k and VC_k are area (ha) and ESV coefficient for the LULC class k, ESV_i is the total ecosystem services for the grid cell ith, and A_{ik} is grid area (ha) of land use k in the grid cell ith.

Vegetation drought index

There are different notions of drought depending on consideration aspects, e.g., meteorological drought, hydrological drought, vegetation drought, and socio-economic drought (Saha et al., 2023). While meteorological drought is mainly assessed by climatic characteristics, vegetation drought is a more relevant criterion for assessing the impact of reservoirs on water stress and ecological regeneration because it includes vegetation greenness and temperature stress dimensions. This research calculated the vegetation health index (VHI, Eq. 3) characterizing vegetation stress under drought conditions (Bento et al., 2018). VHI was derived from Landsat composite image generated from high-quality scenes during the dry season to give a consistent assessment with LULC states. It also, to some extent, reflects vegetation health during the dry season, helping to compare and highlight the obstacles and/or benefits of artificial reservoirs to vegetation health that are frequently emphasized during the dry season. Vegetation and thermal conditions are in turn quantified by the normalized difference vegetation index (NDVI, Eq. 4) and land surface temperature (LST). VHI comprises the vegetation condition index (VCI, Eq. 5) and thermal condition index (TCI, Eq. 6), which assumes that drought-stressed vegetation is linked to low NDVI and high LST. The higher the VHI, the more healthy vegetation.

$$VHI = \alpha VCI + (1 - \alpha)TCI \quad (3)$$

$$NDVI = (NIR - Red)/(NIR + Red) \quad (4)$$

$$VCI = (NDVI - NDVI_{min})/(NDVI_{max} - NDVI_{min}) \quad (5)$$

$$TCI = (LST_{max} - LST)/(LST_{max} - LST_{min}) \quad (6)$$

where *Red* is the visible red wavelength (0.63–0.69 µm), *NIR* is the near-infrared wavelength (0.77–0.90 µm), *SWIR1* is the shortwave infrared wavelength (1.55–1.75 µm), $NDVI_{min}$ and $NDVI_{max}$ are the minimum/maximum values of NDVI, LST_{min} and LST_{max} are the minimum/maximum values of LST, and α is a parameter quantifying contribution of each element ($\alpha = 0.5$, indicating equal contribution) (Bento et al., 2018).

Analyzing spatial relationships between surface water and environmental changes

This research strived to investigate the impacts of surface water changes on agricultural expansion and vegetation drought conditions through spatial and multicollinearity analyses. The impacts of reservoirs are supposed to be localized. It means that each reservoir can influence a certain area through water supply to its basin and moisture for neighboring areas by evaporation process rather than entire study areas of whole Rayong province. Therefore, a variable of proximity to reservoirs was selected to represent the influences of surface water changes. Proximity to reservoirs is characterized by Euclidean distance from a specific location to reservoirs and major water surfaces (Eq. 7). Agricultural development was measured by proportion, and vegetation drought was quantified by changes in VHI. Geographically weighted regression (GWR) was adopted to explore local relationships between surface water changes and other variables (Eq. 8). The GWR analyses were conducted on the grid basis of 1 × 1 km square cells, with independent variable of proximity to reservoirs. The dependent variable was in turn considered as agricultural proportion and vegetation health index. The GWR models were analyzed using Golden search for neighborhood selection within 10–20 km to include potential effects. The effect was then assessed by regression coefficient (R^2) and coefficient of proximity to reservoirs. The higher the coefficient, the more significant the influence of water surface changes on each variable.

$$d(p, q) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2} \quad (7)$$

where *d(p, q)* is Euclidean distance between points *p* and *q*, *qi* and *pi* are Euclidean distance starting from the origin of the space (initial point), and *n* is *n*-space.

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i)x_{ik} + \epsilon_i \quad (8)$$

where y_i is dependent variable at location i, $\beta_0(u_i, v_i)$ is regression intercept at location i, with geographic coordinates (u_i, v_i), $\beta_k(u_i, v_i)$ is regression coefficient for the kth independent variable x_{ik} at location i, p is number of independent variables, and ϵ_i is error term at location i.

Results

Land use, land cover changes: 1990–2020

The LULC maps delineated from satellite images depict a clear spatial separation in Rayong, which can be generally characterized by three distinct regions, including coastal urban areas, western agriculture, and forest and plantation on the east side (Fig. 3). The Sankey plot visualizes the major dynamics of LULCC between land cover classes over the periods (Fig. 4 and Supplementary Table S4). In general, the main trends over 30 years in Rayong are an increase in urban areas, water surfaces, forest lands, and intensive agriculture and a considerable decrease in rainfed arable lands (about two-thirds).

Over the three decades from 1990 to 2020, the study area experienced substantial urbanization in the coastal areas and northwest. It increased by approximately 119%, from only 4.41% (16,253 ha) in 1990 to 9.64% (35,537 ha) in 2020. Urban encroachment primarily occurred on cultivated lands rather than other land uses, with arable lands deemed more affected than intensive arable lands.

In terms of total areas, forests and plantations were slightly expanded by about 25.5%, mainly on the eastern plains. Yet, there were a relatively dynamic LULC transition within it between three LULC types of forest lands, rainfed arable lands, and intensive arable lands. For example, there was 43,864 ha of forest lands occupied by agricultural lands, while about 56,415 ha of agricultural lands were converted into forest plantations at the same time (1990–2000). This trend continued similarly in the following two periods.

Though cultivated lands (i.e., rainfed and intensive arable lands) only show a steady narrowing trend,

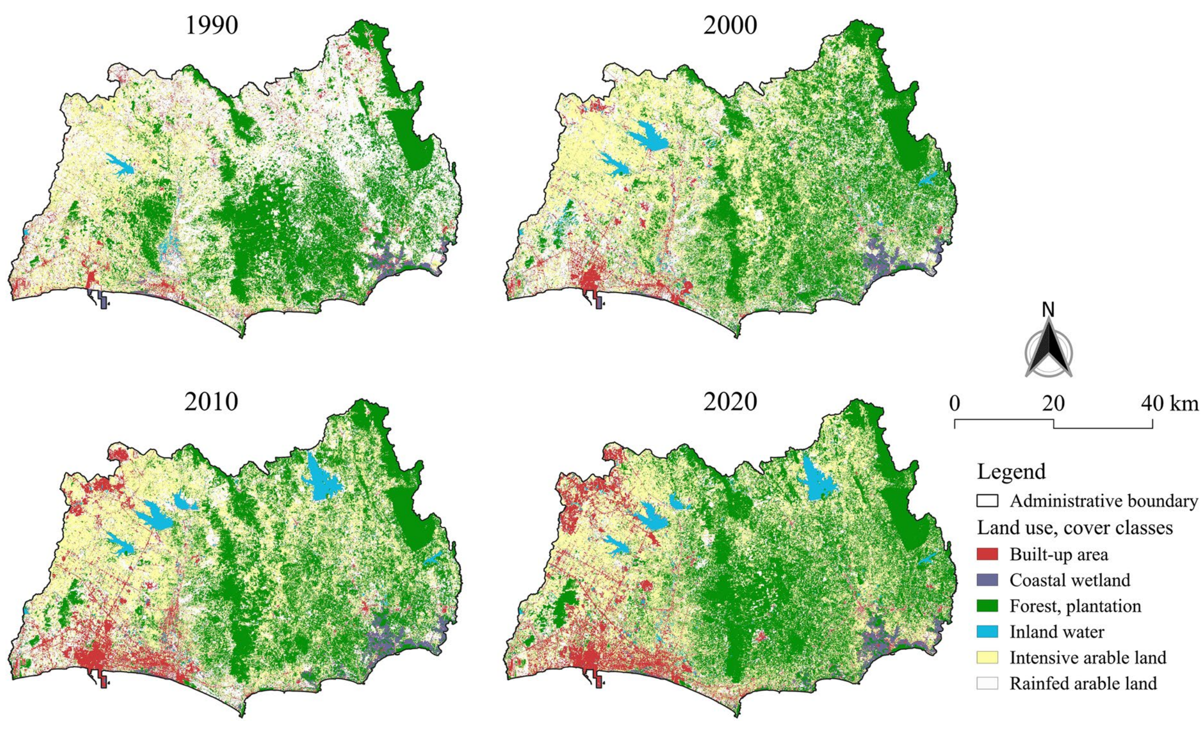

Fig. 3 LULC maps classified from Landsat images from 1990 to 2020, depicting spatial distribution and expansion over time

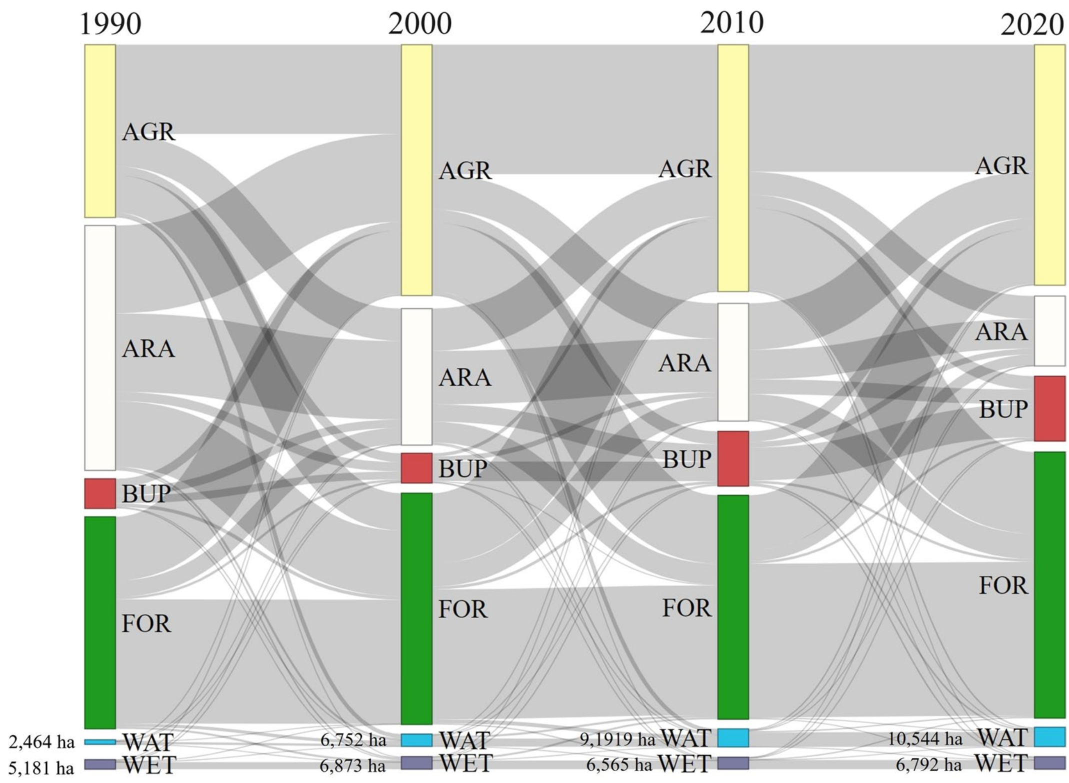

Fig. 4 Sankey plot shows LULC structures in each year and LULC transitions between categories over the periods, highlighting conversion between and within LULC types. Specific converted area between LULC types and years is given in Supplementary Table S4

about 25.7% over 30 years, their transitions were relatively dynamic for each period. More explicitly, rainfed arable lands consistently diminished at a relatively high rate (~40%) in the periods of 1990–2000 and 2010–2020, while this rate was only around 13.8% in the middle period (2000–2010). On the contrary, intensive arable lands substantially widened in the first period, about 45.1% (1990–2000). They were then dominated slightly by less than 3% for each subsequent period. The transitions in cultivated lands were apparently observed in the Prasae river basin, with a considerable decrease in rainfed agriculture.

Water surface expansion can be clearly observed for each period, corresponding to an increase about 328% compared to surface water at the beginning. There was only one reservoir (Dok Krai) in 1990. The estimated total surface was only about 2464 ha (0.67%). The surface water was substantially expanded up to 6752 ha after 10 years (2000) by two reservoirs of Nong Pla Lhai in the Rayong river basin and Khao Chuk reservoir in the east of the province. In the next period (2000–2010), it witnessed two additional reservoirs—another small artificial lake in the Rayong basin (Klong Yai) and the most extensive reservoir of Ban Khao in the Prasae river basin (Fig. 3). The total surface water reached 9919 ha wide in 2010, which likely supplies adequate water for the major cultivation areas. In the final period (2010–2020), the principal irrigation projects were deemed relatively complete. It only increased slightly by 624 ha to reach 10,544 ha of surface water in 2020. The construction of reservoirs mostly affected intensive arable lands and forest/plantations. For example, the accumulative proportion of intensive arable lands and forest/plantations accounted for 77% and 84.5% of total lands for reservoir construction in 1990–2000 and 2000–2010.

Changes in ecosystem service values

Along with LULC changes, ecosystem service values also varied over time (Table 2). The total ESV

Table 2 ESV changes in Rayong province (unit: thousand 2020 USD)

LULC	ESV (thousand 2020 USD)				Changes (%)			
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020
ARA	8315	4634	3996	2376	−44.27	−13.76	−40.54	−71.42
BUP	340	342	627	743	0.50	83.54	18.56	118.69
AGR	8233	8983	8695	10,336	9.11	−3.21	18.87	25.54
FOR	6489	9419	9268	9032	45.14	−1.60	−2.55	39.19
WAT	393	1077	1582	1683	174.06	46.91	6.42	328.46
WET	1696	2249	2149	2223	32.65	−4.48	3.45	31.08
Total	**25,466**	**26,704**	**26,317**	**26,393**	**4.86**	**−1.45**	**0.29**	**3.64**

in Rayong was about 25,466 thousand 2020 USD in 1990, and it reached its maximum ESV in 2000 after a substantial increase of 4.86% to 26,704 thousand 2020 USD. There was a dip in ESV in the next period when it dropped 1.45% to approximately 26,317 thousand 2020 USD. However, it then recovered by taking an increase of 0.29% and stabilized at 26,393 thousand 2020 USD at the end of the period. The net increase in ESV throughout the period was still positive at a level of 3.64%.

The changes in ESV were constituted by significant shifts in water surfaces (WAT, 328.46%), built-up (BUP, 118.69%), and rainfed arable land (ARA, −71.42%). The alternations of water surfaces (+174.06%) and rainfed arable land (−44.27%) were more prominent in the first period, while urban development was highest in the second period (2000–2010), approximately + 83.54%. Although there were variations in the shared proportion of ESV from LULC categories, the ESV is primarily contributed by intensive arable land and forest/plantations, with higher than one-third for each category. The water surface proportion improved from only about 1.54% in 1990 to 6.38% in 2020.

The trend of ESV throughout the periods for basins is depicted in Fig. 5, which shows prominent spatial division in ESV changes. The majority of western basins, i.e., DK, RYB, and NPL, experienced a decline in ESV except for the contiguous areas of reservoirs in the north. In contrast, the north

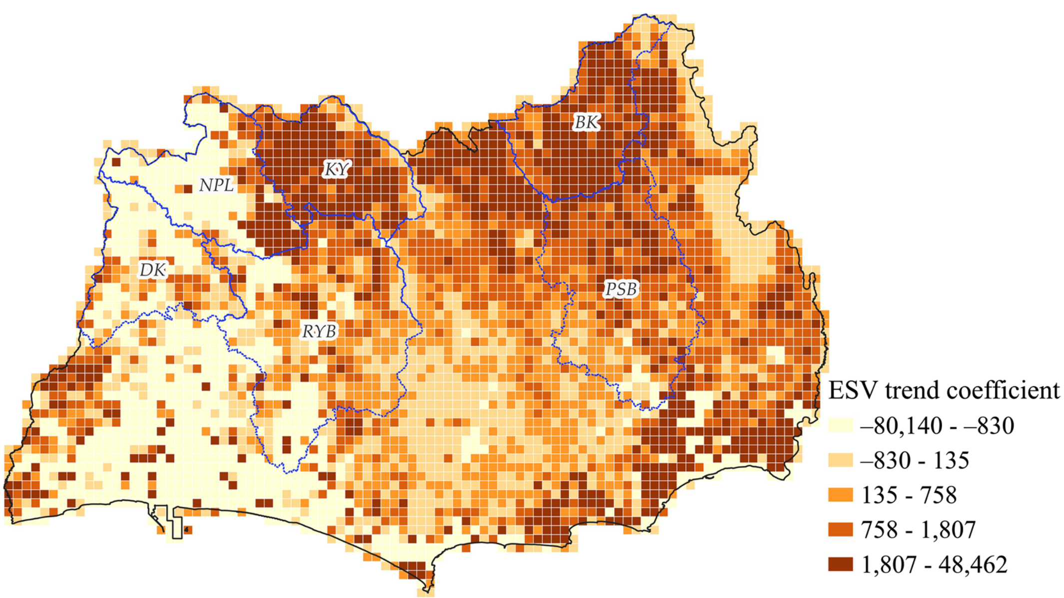

Fig. 5 Linear trend coefficients of total ESV on square-grid between 1990 and 2020 in Rayong province (unit: 2020 USD). Positive coefficients present improvement trend

and northeast basins (KY, BK, and PSB) exhibit an improvement. Moreover, these improvements also spread to their neighboring areas in the north and east regions. For example, the transfer area between RYB and PSB reveals advancement in the ESV trend. It is, however, more modest compared to the intra-basin areas, where the annual increase can hit approximately 50,000 2020 USD per year.

Alleviation of vegetation drought conditions

Vegetation health generally enhanced over time, yet exhibited varying trends across regions (Fig. 6). The vegetation health under drought conditions greatly improved during the first two decades and slightly degraded in the last period. VHI is highly sensitive to the high thermal environment induced by urban agglomeration in the southwest area. Therefore, the overall trend of vegetation health in the entire Rayong exhibited a decline, decreasing from 60.87 to 56.43 because of the average of vegetation in the western metropolitan area. Yet, a particular region-by-region consideration revealed that vegetation health significantly improved in the northeast of the province (Fig. 6). For example, the health of vegetation coverage in KY, BK, and PSB revealed an increasing trend with the highest VHI values found in the middle of the period. Conversely, the western basins of NPL, DK, and RYB suffered from vegetation drought stress, as evidenced by reductions in VHI values of 9.18, 8.12, and 7.12, respectively.

Impacts of water expansion on LULCC and drought reversal

Expansion of reservoirs is deemed to increase water availability for agriculture and local evaporation, thereby stimulating the expansion of intensive agriculture and reducing vegetation drought. The general linear regression model for the entire study areas between changes in agricultural proportion, vegetation health, and proximity to reservoirs, however, yielded relatively low coefficient of determination (R^2) for both agricultural lands vegetation health. It is caused by localized effects of artificial reservoirs on agriculture extension and vegetation health improvement, which is proven by the GWR results (Fig. 7). There are two contributing factors: (1) agricultural development in this region is also governed by policy rather than relying solely on irrigation, and (2) the area has experienced rapid urban development, which can confound the assessment of vegetation drought for entire study area. Moreover, the diversity of terrain also limit impacts in mountainous and remote areas from reservoirs.

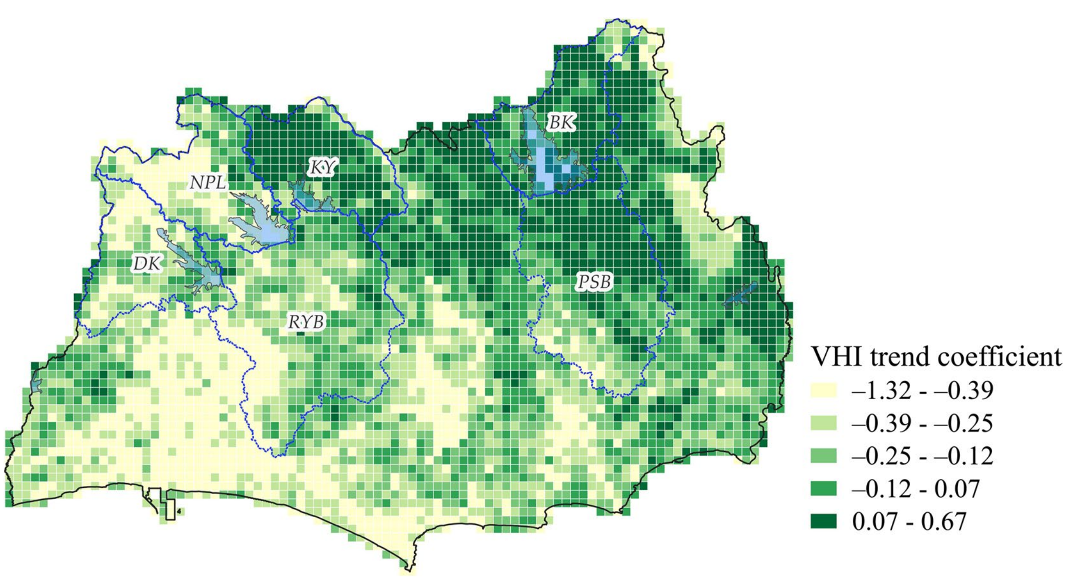

Fig. 6 Linear trend coefficients of VHI from 1990 to 2020. Positive coefficients present improvement trend

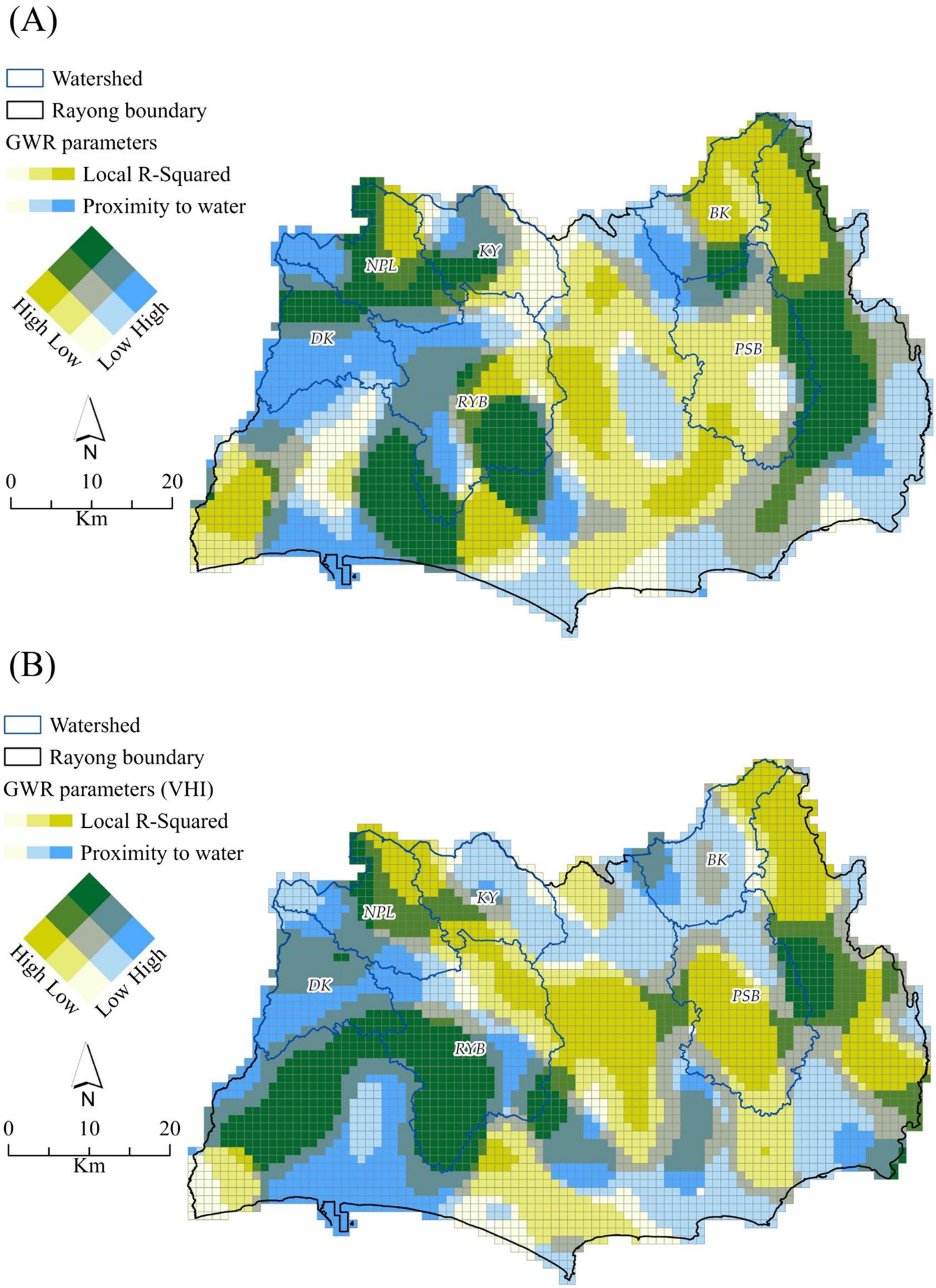

Fig. 7 Bivariate maps illustrate local R-squared and regression coefficients of proximity to water, presenting relationships between distance to reservoirs and changes in (**A**) agricultural proportion and (**B**) vegetation health

The impacts of proximity to reservoirs on agricultural production and vegetation drought are localized in some specific regions and basins rather than the entire province, with localized coefficient of determination (R^2) can reach maximum values of 0.53 and 0.57 for agricultural extension and vegetation health improvement, respectively. Meanwhile, the low impact areas have very low R^2 values, about –0.13 and – 0.54 for agriculture and vegetation health, respectively. It explains why the general regression models on entire Rayong returned very low R^2 because it has to neutralize the opposing effects between the regions above. The localized effects of reservoirs on agriculture and vegetation health are relatively comparable in terms of spatial patterns, which can be divided into subregions with strong influences from reservoirs' impacts on agriculture and drought reduction (Fig. 7). More specifically, the yellow subregions having high regression coefficients (R^2) and low proximity to reservoirs mean the shortening of distance to reservoirs increases agriculture and reduces vegetation drought. For example, the reservoirs positively affect agriculture and drought conditions in BK, PSB, upper RYB, and upper NPL. These positive effects are even more widespread and extend far beyond the immediate vicinity of the reservoirs to a large area between RYB and PSB. In contrast, the blue subregions with low regression coefficients (R^2) are supposed to have low influences from reservoir projects. For example, although the lower BK and RYB have reduced the distance to reservoirs, they constrain both agricultural expansion and drought mitigation because of urban development in Rayong municipality.

Discussions

Surface water changes facilitating agricultural expansion and drought reduction

The LULCC in Rayong over the past 30 years exhibited strongly dynamic changes among LULC categories, but they are generally positive. Rainfed agriculture was gradually replaced by intensive agriculture, which benefits incomes and food security. An expansion of forests and plantations could significantly contribute to environmental assets. It cannot be missed the most drastic expansion of surface water by nearly 11% every year by several artificial reservoirs across the province ("Land use, land cover changes: 1990–2020" section). Surface water expansion was an effort by the government to repel water scarcity in Rayong province through artificial reservoirs. It was proved to induce LULCC in this region, especially for the expansion of intensive arable lands, which is significantly linked to proximity to reservoirs ("Impacts of water expansion on LULCC and drought reversal" section).

Surface water expansion also facilitates ecological regeneration by improving water availability. Indeed, expanding water surfaces and vegetation has advanced the total ecological assets represented by ESV by 3.64% ("Changes in ecosystem service values" section). It can embrace diverse services and benefits to the environment and local communities. One of the benefits evaluated is vegetation health, which implies both ecological regeneration through greening and reduction of vegetation water stress or vegetation drought. It certainly proved the positive impacts of reservoirs on vegetation drought mitigation and spatial heterogeneity of water availability. The controls of water availability in drought conditions mostly exceed local boundaries and imprint on their catchments and watersheds; however, the effects are localized rather than the entire Rayong ("Impacts of water expansion on LULCC and drought reversal" section). The diversity in terms of terrain and human activities significantly regulate the effects. For example, higher terrain areas are more susceptible to drought, and it is even hard to improve by artificial reservoirs. Meanwhile, the lower-lying area are easy to benefit from the irrigation projects, except for urban areas in the west because they have dense population with high water demands for domestic and production. It may lead to water shortage for plants inducing low vegetation health in this urbanized areas. It delineated the areas, taking advantage of the current irrigation and reservoirs in agricultural production and drought alleviation, underscored by a high GWR coefficient. At the same time, it emphasized areas still hindered by drought conditions but have not received benefits from the current irrigation system with a low GWR coefficient. It should be noted that the principal economic plants in Rayong include rubber, pineapple, cassava, rice, oil palm, sugarcane, and various fruits (e.g., durian, longan, and mangosteen). Except cassava and pineapple, they have relatively high water demand. Although they have their own drought tolerance mechanisms (except rice and manosteen with low drought tolerance), which are mainly based on growth control, stomatal closure, and increased use of groundwater uptake in deep-rooted plants. But as mentioned, this area has limited groundwater resources, so the impact of drought on these plants and their yields can be significant. In the context of water demand for domestic uses, industrial production, and agricultural cultivation is increased by 10–20% per year for each sector, while the water resources are still limited with the current reservoirs (Soytong et al., 2023). These spatial heterogeneities revealed from GWR analysis are critical information for local authorities regarding sufficient water allocation, especially in areas facing drought conditions (Suksaroj et al., 2024).

The GWR models were successfully isolated the local effects of reservoirs on agricultural extension and drought mitigation with the local R^2 higher than that assessed by general regression. Yet, it should be noted that the localized R^2 values are still limited to the average level (approximately 0.5–0.6) for the distance to water as the only independent variable as we only focusses on the impacts of reservoirs in this study. It implies that agricultural expansion and vegetation drought may be influenced by other factors that should be investigated in future studies, such as terrain, rainfall, urban development, and planning.

The ESV is a relevant method for quantifying ecological impacts caused by LULCC, which conveniently provides quantitative information for planners and the general public. Its spatial pattern is relatively localized within the ecosystem, which may not fully reflect the flows of ecosystem services. For example, constructing a reservoir can create a habitat for aquatic ecosystems and recreation activities at the reservoir itself. Nevertheless, the ESV struggles to adequately capture other ecosystem-transboundary benefits, such as downstream flood mitigation, groundwater recharge, water supply, and food production. Individual ecosystem services and benefits should be investigated separately by hydrological models and integrated models for ecosystem service assessment (e.g., InVEST and LUCI), to better understand the mechanisms and distribution of benefits and negative impacts from artificial reservoirs in diverse aspects. It should be noted that the large reservoir projects can disturb indigenous communities and alter their livelihoods. It is necessary to encourage social engagement and assessments to gain in-depth knowledge of potentials and trade-offs between local stakeholders, thereby leading to better water resource management planning in a participatory management manner.

Policy relevance of Thailand's water resource management

Thailand and the eastern region are well-known as regions with limited water resources and extreme drought conditions, yet the economy mainly depends on agricultural production and many industrial activities. Thus, water management has evolved along with its development. In the nineteenth century, water management was focused on "*supply-side management*" regime, which mainly developed canals for transportation and agriculture (Sethaputra et al., 2001). During this period, it still relied on natural water resources. Yet, building reservoirs and spreading irrigation systems were more focused in the last century because of population pressure (Bastakoti & Shivakoti, 2008). Several national plans, i.e., the sixth national plan (1987–1991), the seventh national plan (1992–1996), and the eighth national plan (1997–2001), were promulgated to support this strategy (Sethaputra et al., 2001). Therefore, this region witnessed the explosion of reservoirs during the period of 1990–2000 ("Land use, land cover changes: 1990–2020" section). The construction of new reservoirs was still focused on later periods. Nevertheless, the supply-side strategy gradually showed its limitations because population and economic explosions can induce water resources to reach the limits (Bastakoti & Shivakoti, 2008). The "*demand-side*" management was enacted, and it became the principal management regime in the later periods (Bastakoti & Shivakoti, 2008; Tangworachai et al., 2023). It is characterized by water allocation and conservation, which integrate organizational and institutional interventions to save costs and promote sustainability rather than investment in additional water supply projects (Chaowiwat et al., 2016).

The region therefore experienced a stable expansion in the middle and current periods. Although the Royal Irrigation Department evaluates that the current water allocation from reservoirs in EEC can meet demands for all sectors, it only occurs during normal years. The dry years pose a big challenge for sufficient water supply, especially for rice paddy fields and farmers (OECD, 2022). The development of agriculture in this region, to some extent, is supposed to be a challenge for local water supply, which requires consideration of plant structure and manner of water management to suitably use water resources. The current water resources development and management project for EEC (2020–2037) comprises five aspects of water resources development, water demand management, prevention and mitigation plan, water quality management, and measures to cope with water shortage (The Eastern Economic Corridor 2020). In addition to construction solutions implemented over the past decades, the current strategy more focuses on non-structural solutions. It is to manage water demand and reduce new reservoir projects, which is the reason why the water expansion in the last period (2010–2020) was the lowest. It also focuses on strengthening local capacity to jointly allocate water resources rationally and manage water resources sustainably. Institutional regulations have also been issued to regulate each type of water use and determine water fees for industry, tourism, electricity production, and water supply to promote more efficient water use (Thailand development research institute, 2024). Community-based water management solutions, including climate change, and integrating nature-based solutions in water management are also addressed in long-term strategies. Desalination in Rayong is also an ambitious vision to solve the regional water shortage in the long-term period (Phadungsontikul, 2022; Suksaroj et al., 2024). These strategies are expected to significantly contribute to regional water sustainable use efforts.

Conclusion

Over the past three decades, Rayong province has experienced a dynamic LULCC, with a substantial shift observed in the first decade compared to the last periods. In this complex LULCC system, the principal trends were urbanization, agricultural expansion, and increased surface water. Vegetation extension by forests, plantations, and intensive agriculture clearly occurred in the main river basins, while rainfed agriculture was gradually replaced by the above land cover, approximately 2.4% per year. The most prominent change was an increase in surface water with five artificial reservoirs. The total surface water area gained 10,054 ha. The reservoir construction mainly affected rainfed and intensive agriculture and forest lands. LULCC was supposed to have positive benefits to the ecological environment, reflected by an increase of 3.64% in the total ESV. Significant changes in ESV were also found in both headwater and downstream basins.

The regional vegetation drought conditions monitored by VHI at the beginning of the period were relatively severe. These conditions were significantly improved in the KY, BK, and PSB. However, the general trend effects were more moderate because of urban dryness in the southwest areas with an intensive urban agglomeration.

Surface water changes were determined to have significant benefits for agricultural expansion and drought alleviation, as revealed by the GWR analysis. The relationships between water changes and agriculture and vegetation drought spread on the entire river basins. These spatial relationships highlight beneficial areas of the reservoirs and hindered areas, where should have sufficient water allocation strategies to cope with increasingly extreme droughts under impacts of climate change.

The findings of this study revealed the impacts of reservoir projects on both LULCC and vegetation drought reduction, which have important implications for water resource management and sustainable development in Rayong province. The expansion of surface water through reservoir construction has led to significant improvements in agricultural expansion, drought mitigation, and ecosystem service values. However, the spatial heterogeneity of these impacts highlights the need for targeted water allocation strategies to address the remaining areas facing water scarcity. Future research should focus on assessing the long-term impacts of artificial reservoirs and developing sustainable water management strategies that balance the needs of agriculture, industry, and the environment.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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