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Review article

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Anthropogenic impacts on the Yellow River Basin

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Abstract

The Yellow River Basin supports a population of 200 million people and contains 15% of arable land in China. Water scarcity in the region is being exacerbated by climate change and human activities. In this Review, we discuss anthropogenic impacts on the hydrological cycle and sediment dynamics of the Yellow River since the 1950s. The Yellow River had one of the largest sediment loads in the world, peaking at 2.1 Gt yr^{-1} in 1958. Such high sediment loads elevated flood risk; therefore, reservoirs, conservation and revegetation projects were implemented, reducing sediment transport by 90% since the 1980s. However, these efforts also impacted the hydrology of the Yellow River Basin, leading to an increase in evapotranspiration fluxes (1.79 mm yr^{-2}, 1980–2020) and reduced runoff. In addition, human water use has increased by 15.8% since the 1980s. The resulting reductions in soil water storage and intensification of the vertical water cycle foreshadow potential resource crises and will potentially lead to irreversible ecosystem degradation. Predicting the outcomes of water management policies and engineering projects is essential but highly complex owing to feedback loops and interactions between human activities and hydrological changes. Addressing these challenges, which are also faced by other arid-region rivers, will require dynamic monitoring of water storage and improved understanding of human–hydrological interactions.

Sections

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Introduction

Anthropogenic pressures driven by population growth, economic development and rising water demand[1–3] are increasingly threatening the integrity and sustainability of river basin ecosystems[4–6], putting the future of over 2 billion people living in drylands at risk[7,8]. The Yellow River (also called the Huanghe) is the fifth-longest river in the world and spans arid to semi-arid regions (Supplementary ws. 1 and 2). However, the annual water discharge of the Yellow River is disproportionately lower than that of other major rivers. Anthropogenic impacts have profoundly altered — and continue to shape — the hydrological cycle, soil erosion, sediment transport and sediment deposition in the Yellow River Basin (YRB)[9]. Ecosystem degradation in the source region of the Yellow River[10], severe soil erosion in the middle reaches, and depleted downstream streamflow have resulted in multiple socioeconomic stresses alongside water resources conflicts and eco-economic poverty[11–14].

The Yellow River has one of the highest sediment loads in the world[13,15–17]. The susceptibility of loess to erosion, combined with periodic extreme rainfall events, sparse vegetation and long-term and intensive farming activities, have resulted in severe soil erosion on the Loess Plateau in the middle reaches of the Yellow River. This soil erosion contributes to the high sediment loads, increasing the risk of flooding[16,18]. Since the 1980s, reservoir operation, soil conservation and large-scale reforestation have reduced sediment flux by over 90% (ref. 16). The total water storage of the Yellow River reservoirs (50 billion cubic metres) now exceeds the total annual discharge[9], marking the YRB as a controlled river basin where people effectively regulate its water and sediment[19,20].

The YRB is facing multiple water scarcity challenges. The YRB supports 12% of the national population and 15% of arable land, with merely 2% of China's water resources[21,22]. Water withdrawal has increased to 80% of the Yellow River's annual discharge, leading to perennial flow interruptions in the lower reaches that exceed the threshold for ecological collapse. Efforts to reduce soil erosion through ecological restoration have also increased water consumption[11], primarily driven by enhancement of evapotranspiration[23,24]. In addition, runoff reduction[25] and soil moisture depletion[26] have been observed across the basin (Fig. 1). The ecological, social and economic consequences of diminishing water availability are thus becoming critical issues for the YRB[12,14].

In this Review, we discuss the impacts of human activities on water and sediment dynamics in the YRB. First, we outline long-term trends and the magnitude of changes in water flow and sediment load in the YRB. We then identify changes in human population, water use, land use, vegetation and economy and explore feedback loops between these changes and the basin hydrology. Finally, we discuss areas in which further research is needed to address uncertainties in human–river feedbacks and hydrological outcomes, including the feedback between precipitation and vegetation restoration, links between soil erosion and delta dynamics, and the cascading and lock-in effects of water governance.

Hydrological changes

Various data sources (Supplementary Table 1), including station observations, remote sensing data and reanalysis data, show that the components of the YRB water cycle have changed substantially since the 1950s (Fig. 1). For example, the discharge of the Yellow River has significantly decreased[9,27] at -5.78×10^8 m^3 yr^{-1} during 1950–2020 ($P < 0.01$) without marked changes in precipitation. The vertical water vapour cycle has intensified, with increased evapotranspiration but with soil moisture, groundwater and glacier storage all decreasing[11,27,28]. The rising human demand for water resources has driven a rapid increase in water withdrawals. Expansion in the number and area of reservoirs has also led to an increase in open water bodies, which are then exposed to evaporation[29,30]. Consequently, the water cycle of the YRB has exhibited a decrease in blue water (available surface water and groundwater), an increase in green water flow (evapotranspiration, especially transpiration) and a reduction in green water storage (soil moisture)[31,32], as now discussed.

Precipitation

Long-term average annual precipitation in the YRB is approximately 472.69 ± 94.16 mm yr^{-1}, decreasing from southeast to northwest and predominantly concentrated between May and September[33,34]. During 1960–2000, precipitation in the YRB decreased at −2.21 mm yr^{-2} ($P < 0.05$)[35–38], but subsequently increased with a rate of 3.12 mm yr^{-2} in 2000–2022 ($P < 0.05$) (Fig. 2a). Precipitation thus does not display a clear statistically significant long-term trend. There is substantial spatial variability in precipitation trends across the YRB. For example, precipitation increased in the source reaches of the YRB, its upper regions and the Loess Plateau[39] between 1960 and 2020 but decreased elsewhere in the basin[35,38] (Fig. 2b). In addition, the frequency and concentration of extreme precipitation events in the YRB is increasing[38,40–42]. This increase in extreme events has intensified flood risk and drought vulnerability, making the management of reservoirs and scheduling of water releases more complicated[43].

Evapotranspiration

Between 1980 and 2020, the YRB had an annual average evapotranspiration of approximately 370.69 ± 55.92 mm yr^{-1}. Thus, over 75% of yearly precipitation evaporates[44], which far exceeds the global average (~60%)[45]. Despite marked differences between data sources (Supplementary Table 1), all estimations consistently show an increasing trend in evapotranspiration — with up to 86% of the basin area showing a significant rise ($\alpha = 0.05$) (Fig. 2c,d) whereas soil evaporation exhibits a decreasing trend at −0.42 mm yr^{-2} ($P < 0.01$)[23,46]. This increase in evapotranspiration is attributed primarily to increased temperatures and establishment of vegetation through ecological restoration[24,46]. Irrigation also contributes to the increase in evapotranspiration in the YRB, accounting for up to 44.3% of the total increase in evapotranspiration in areas with large irrigation complexes[41,44,47].

Soil moisture and groundwater

There is substantial variability in estimates of soil moisture in the YRB[48,49]. For instance, during 1980–2020, ERA5 data suggest a decrease in soil moisture, whereas Global Environmental Assessment Model (GLEAM) data show an increase (Fig. 2e). Observations of soil moisture show a decline from 1980, which is particularly pronounced in the middle and lower reaches of the YRB[28,50,51] (Fig. 2f and Supplementary Table 2). This decrease in soil moisture might be attributed partly to enhanced evapotranspiration caused by increased vegetation cover[11,52].

Although available data on groundwater are limited, most results suggest that groundwater in the YRB is declining (Supplementary Table 2). This decrease is driven primarily by intensive groundwater extraction[53,54]. Monitoring wells suggest that there is high spatial heterogeneity in groundwater changes[55]; however, large-scale spatial estimations based on Gravity Recovery and Climate Experiment (GRACE) data show a continuous decline at a rate of approximately −3 mm yr^{-1}

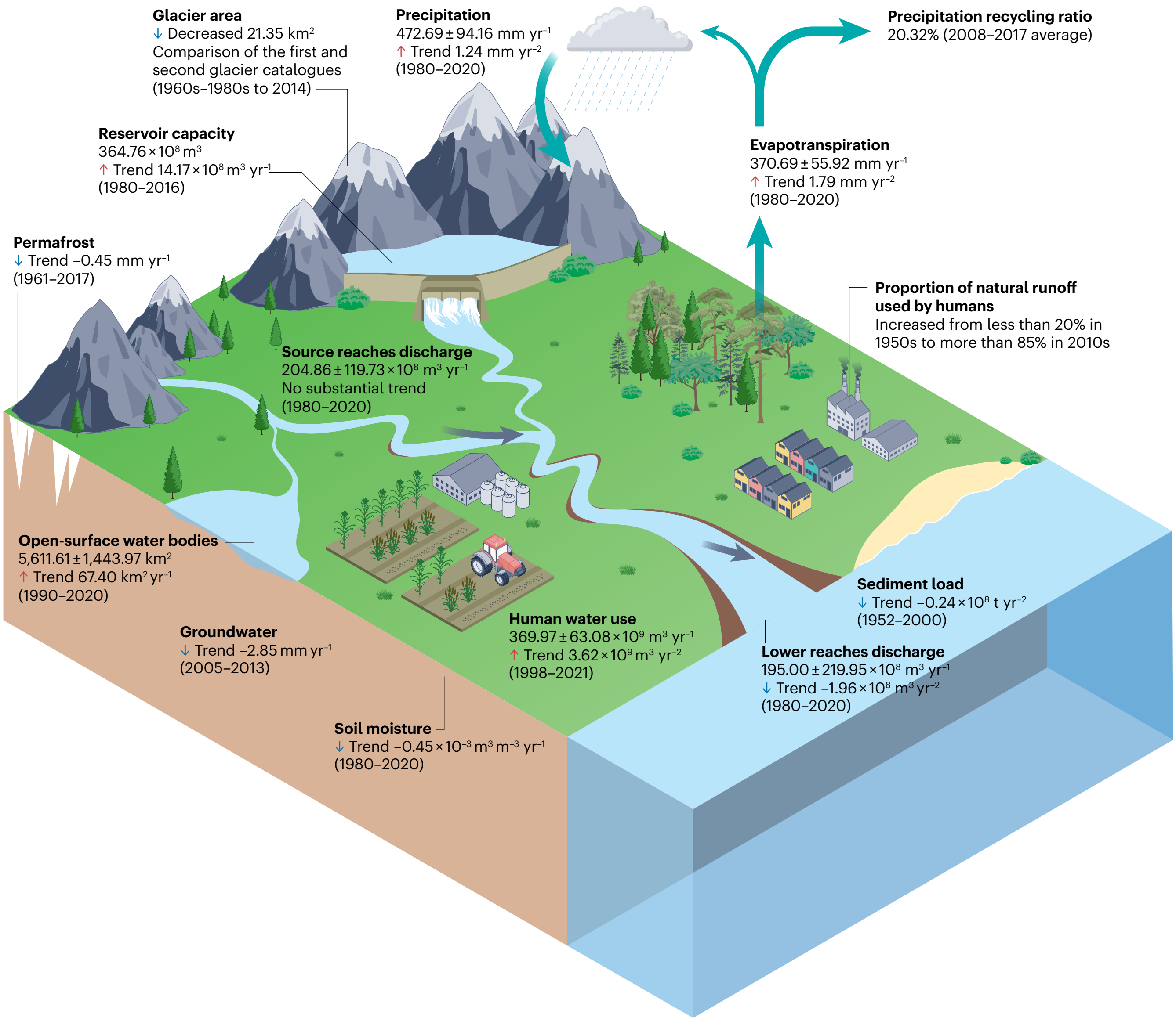

Fig. 1 | The water cycle in the YRB. A schematic diagram of the magnitude and trends (for the period indicated in parentheses) of components of the Yellow River Basin (YRB) water cycle where such information is available and physically meaningful, including precipitation (data are from CN05 (ref. 197)), evapotranspiration (Global Environmental Assessment Model (GLEAM)v3.8 (ref. 198)), soil moisture (ERA5 (ref. 199)), discharge for the source area (recorded at the Tangnaihai hydrological station (Supplementary Table 1)), discharge and sediment load in the lower reaches (recorded at the Lijin station (Supplementary Table 1)), the precipitation recycling ratio (calculated using the Lagrangian moisture tracking model data[200]), human water use (calculated based on the Yellow River Basin Water Resources Bulletin data (Supplementary Table 1)), open-surface water bodies[29], reservoir capacity[9,19], glacier area[65], permafrost depth[66], groundwater[53] and the proportion of human water withdrawals[35]. Many of these components of the YRB water cycle have changed substantially since the 1950s.

in groundwater storage[41,53,55,56]. The decline in groundwater and soil moisture underscores the severity of water resource shortages in the YRB.

Glaciers and open-surface water bodies

The warming climate has reduced glacier area by 21.35 km^2 (1960s–2014) and caused a decreasing trend in permafrost depth of −0.45 mm yr^{-1} (1961–2017) in the source region of the YRB (Fig. 1). Approximately 35–42% of the runoff of the Yellow River originates from the Qinghai-Tibet Plateau[57–61]. Accelerated glacier retreat and permafrost melting alter the timing and magnitude of meltwater inputs, potentially causing seasonal shifts in water availability and exacerbating early spring flooding and late-season low flows[62–64]. Therefore, these changes might weaken water supply capacity and threaten water availability[64–66].

The area of open-surface water bodies, including rivers, lakes, reservoirs and other terrestrial water bodies is increasing. The construction and operation of large reservoirs in the basin to support the increased proportion of discharge used by humans (from less than 20%

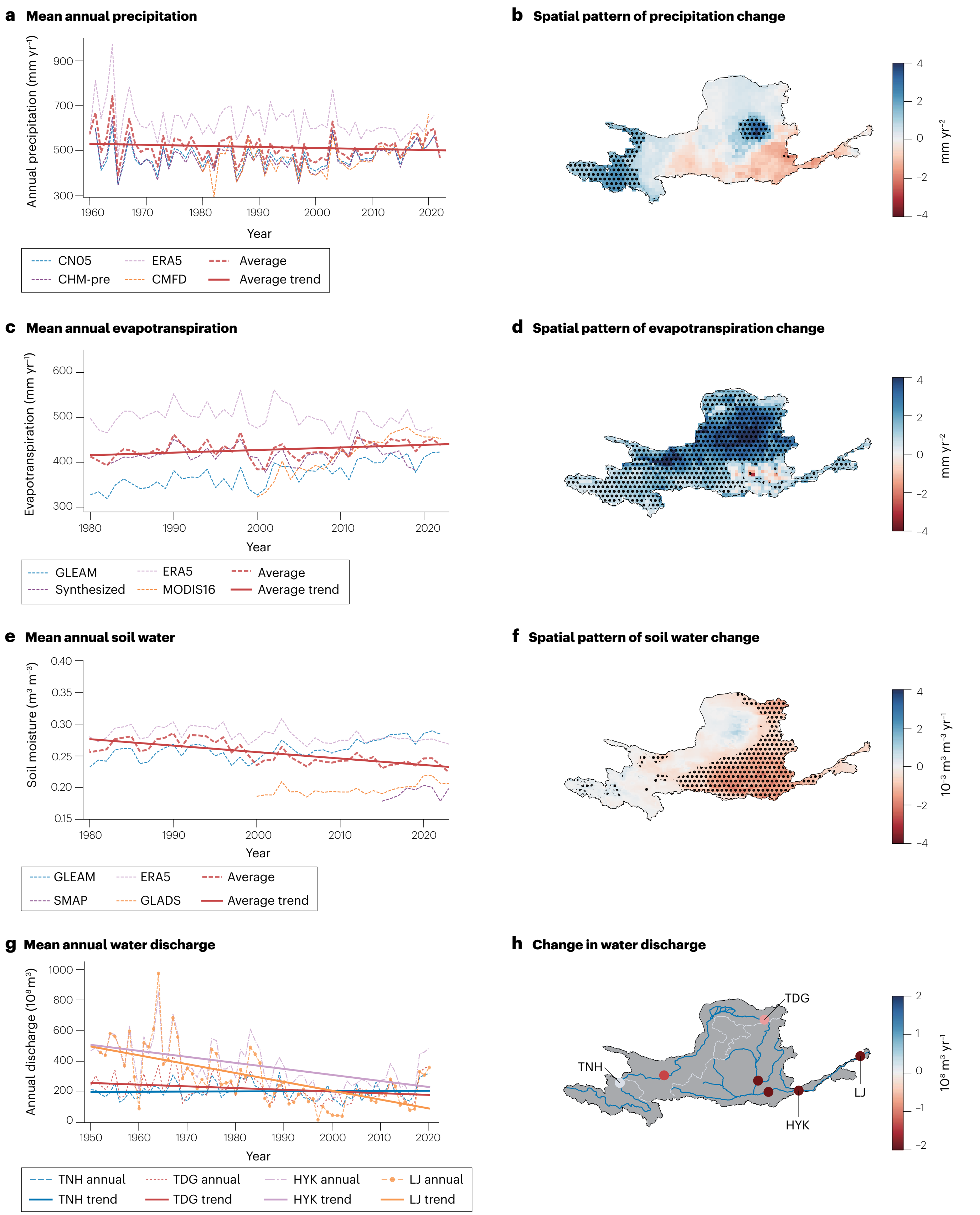
a Mean annual precipitation
Annual precipitation (mm yr⁻¹)
900
700
500
300
1960
1970
1980
1990
2000
2010
2020
Year
CN05
ERA5
Average
CHM-pre
CMFD
Average trend
b Spatial pattern of precipitation change
4
2
0
−2
−4
mm yr⁻²
c Mean annual evapotranspiration
Evapotranspiration (mm yr⁻¹)
600
500
400
300
1980
1990
2000
2010
2020
Year
GLEAM
ERA5
Average
Synthesized
MODIS16
Average trend
d Spatial pattern of evapotranspiration change
4
2
0
−2
−4
mm yr⁻²
e Mean annual soil water
Soil moisture (m³ m⁻³)
0.40
0.35
0.30
0.25
0.20
0.15
1980
1990
2000
2010
2020
Year
GLEAM
ERA5
Average
SMAP
GLADS
Average trend
f Spatial pattern of soil water change
4
2
0
−2
−4
10⁻³ m³ m⁻³ yr⁻¹
g Mean annual water discharge
Annual discharge (10⁸ m³)
1000
800
600
400
200
0
1950
1960
1970
1980
1990
2000
2010
2020
Year
TNH annual
TDG annual
HYK annual
LJ annual
TNH trend
TDG trend
HYK trend
LJ trend
h Change in water discharge
TDG
TNH
HYK
LJ
2
1
0
−1
−2
10⁸ m³ yr⁻¹

Fig. 2 | Time series and trends in water cycle components. **a**, A time series of annual mean precipitation in the Yellow River Basin (YRB) (the data are from CN05 (refs. 197,201), ERA5 (ref. 199), CHM-pre[202] and CMFD[203]). The red dashed and solid lines show the mean values of multiple datasets and corresponding trend lines, respectively. **b**, The spatial patterns of precipitation change between 1980 and 2022 in the YRB (the data are from CN05 (ref. 197)), the stippled area indicates regions with a statistically significant change ($\alpha = 0.05$). **c**, Same as in **a** but for the mean annual evapotranspiration (the data are from the Global Environmental Assessment Model (GLEAM)[204], ERA5 (ref. 199), MODIS16 (ref. 205) and a synthesized data package[206]). **d**, Same as in **b** but for evapotranspiration (the data are from GLEAM v3.8 (ref. 198)). **e**, Same as in **a** but for mean annual soil water (the data are from GLEAM[204], ERA5 (ref. 199), SMAP[207] and GLADS[208]). **f**, Same as in **b** but for soil moisture (the data are from ERA5 (ref. 199)). **g**, A time series of mean annual water discharge (dashed line) and the average trend (solid line) measured at hydrological stations at Tangnaihai (TNH), Toudaoguai (TDG), Huayuankou (HYK) and Lijin (LJ). The data are derived from the Yellow River Conservancy Commission (Supplementary Table 1). **h**, The location of the hydrological stations in **g** and the change in water discharge measured at each between 1960 and 2020. The YRB has exhibited no marked changes in precipitation patterns, significant evapotranspiration increases, soil moisture depletion and changes in discharge that differ between upstream and downstream regions.

in the 1950s to over 85% in 2010s) has led to a rapid increase in the capacity of open water bodies[29]. Remote sensing data show that between 1990 and 2020 the area of open-surface water bodies increased by 27.5% during floods and 58.9% during the dry season[29]. The five largest reservoirs along the main course of the Yellow River account for 9.48% of the total area of water bodies in the basin[29,35]. The total capacity of the YRB reservoirs exceeds the average annual discharge of the Yellow River[67,68].

River discharge

River discharge in the YRB has decreased, owing to increased evapotranspiration and changes in land use[35,44] (Fig. 2g). Between 1950 and 2020, there was no substantial overall decline in discharge in the upper reaches and source regions of the Yellow River. Conversely, discharge in the middle and lower reaches declined at -3.93×10^8 m^3 yr^{-1} and -5.78×10^8 m^3 yr^{-1} ($P < 0.01$), respectively. This decline has gradually stabilized since the year 2000[9,35,69] (Fig. 2h). Observed changes in actual discharge are linked not only to a warmer and drier climate, but also to increased human water consumption and changes in vegetation cover[9,37,41]. Hydrological data from multiple stations along the river indicate that downstream discharge is lower than upstream discharge owing to human water use[27,41].

Vegetation restoration alters runoff by direct water consumption and through vegetation–climate feedbacks. Since the 1980s, the Yellow River has undergone extensive vegetation restoration[70–72], and it has long been believed that increased vegetation cover reduces runoff, alters the distribution of precipitation and increases evapotranspiration[73]. However, the importance of feedbacks between vegetation and the atmosphere is being increasingly recognized. Observational data and numerical simulations reveal that increased vegetation cover intensifies land–atmosphere interactions, thereby enhancing the local water cycle and increasing precipitation[74,75]. Long-term observations (1980–2020) exhibit robust increasing trends (2.76 mm yr^{-2}) of surface water yield over 82.3% of the Loess Plateau since revegetation commenced[39]. This seemingly counterintuitive trend highlights the importance of considering vegetation–climate feedbacks in assessing hydrological responses to large-scale vegetation changes and restoration efforts.

Changing sediment load and deposition

The Yellow River has historically been characterized by an extremely high sediment load[5,15,16]. This section outlines the temporal and spatial patterns in sediment loads and the effects of efforts to reduce the sediment load.

Temporal trends

The Yellow River used to have one of the largest sediment loads in the world[5] (Supplementary Fig. 3). Before 1000 A.D.[15,16,76,77], sediment load in the Yellow River was at a level of approximately 0.2 Gt yr^{-1} (Fig. 3a) but then began to gradually increase owing to increasing soil erosion caused by cultivation and land use change on the Loess Plateau. In the 1950s, sediment concentrations in the Yellow River surpassed 40 kg m^{-3} (refs. 78,79) (Fig. 3b) with an average annual sediment load of 1.6 Gt yr^{-1}. The sediment load peaked in 1958 at 2.1 Gt, far exceeding the natural baseline conditions[15,76,77,80]. The average sediment load of the Yellow River during 1961–1990 was 0.883 Gt yr^{-1}, accounting for 5–10% of global sediment flux into the oceans[5,81–83].

The once characteristically high sediment load of the Yellow River has diminished substantially owing to anthropogenic changes, including vegetation restoration, landscape engineering and the construction of reservoirs and check dams[16]. The sediment load of the Yellow River declined at an average rate of -0.024 Gt yr^{-2} during the second half of the twentieth century. The average annual sediment load after 2000 is 0.148 Gt, only 10% of that observed in the 1950s. In addition, the sediment concentration decreased by 75% after 2000 (Fig. 3a,b).

Spatial heterogeneity

Large quantities of sediment are transported from the Loess Plateau into the Yellow River[16,17], which accumulate mostly in the lower reaches of the river and its estuary. Although over 60% of the Yellow River's water discharge originates from the YRB above Lanzhou[60], the sediment load at Lanzhou is merely 8% of that from the lower reach (Fig. 3c). The Loess Plateau in the middle reach contributes 90% of the sediment load entering the Yellow River[16,70,83,84]. In the lower reach of the Yellow River, the channel gradient decreases, leading to substantial sediment deposition[85]. Therefore, levees have been constructed in the lower reaches to control floods[17]. This intense sediment deposition has elevated the riverbed by over 10 m above the adjacent alluvial plain[18,86], forming what is commonly known as a 'hanging river' constrained within levees[18] (Supplementary Fig. 1). This phenomenon has led to frequent flooding, breaching and diversion events on the downstream Yellow River floodplain[18,76,87,88]. Moreover, the river channel continues to meander and silt up between the levees, with breaching of the elevated river further threatening the floodplain within, and outside, the levees[89–91].

Sediment deposition in the lower reaches of the Yellow River has also led to the formation of alluvial plains and deltas. The modern Yellow River Delta, which began forming in 1855 following diversion of the Yellow River to its current estuary, has created approximately 2.7×10^3 km^2 of new land[92]. During the last 6,000 years, sediment deposition has pushed the coastline 60 km into the Bohai Sea[93]. It is also estimated that over 530 Gt of sediment have been deposited in the alluvial plains and deltas since 1128 A.D.[77]. This deltaic expansion has created land resources and formed ecologically valuable wetlands with high

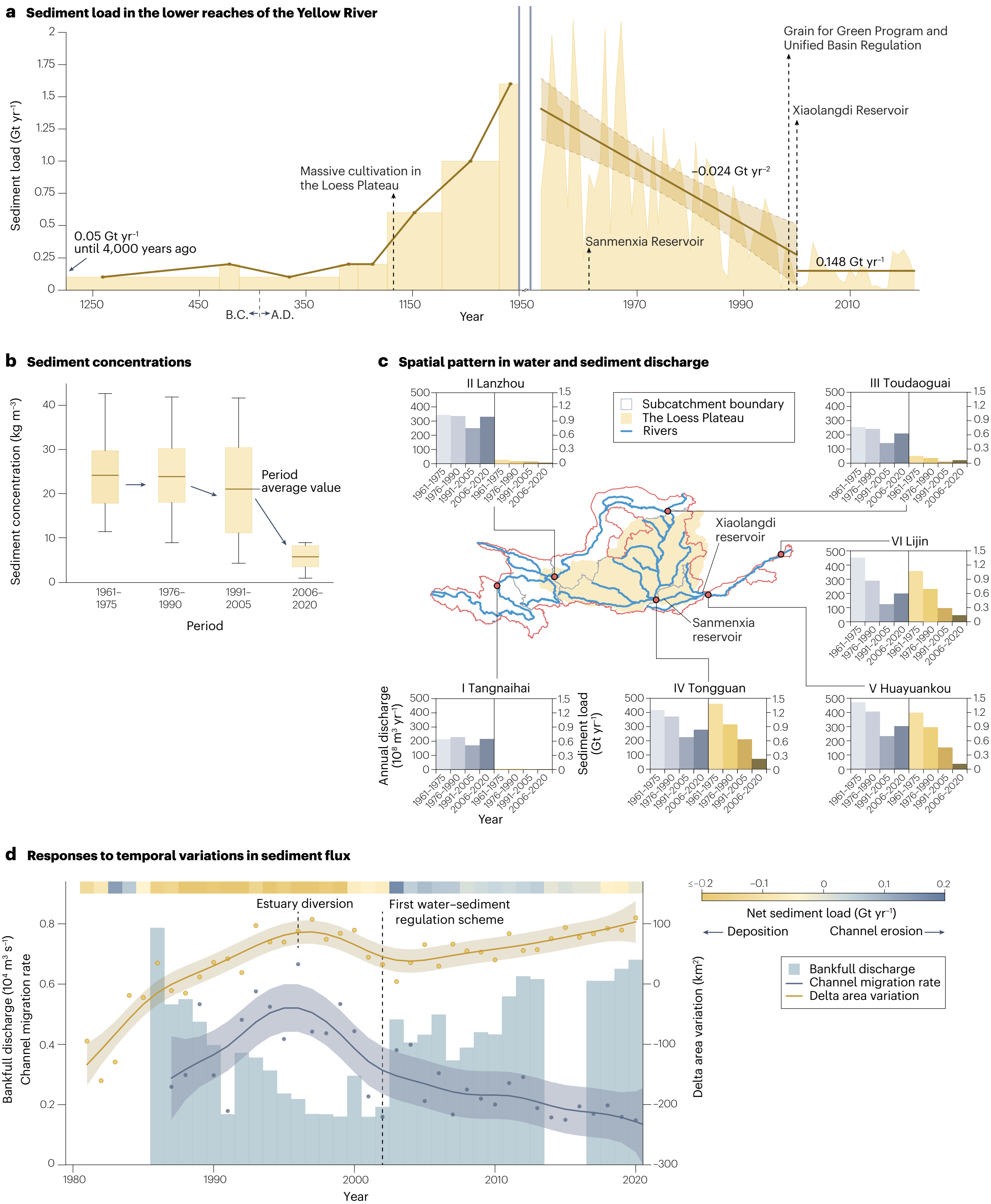
a Sediment load in the lower reaches of the Yellow River
Sediment load (Gt yr−1)
0.05 Gt yr−1 until 4,000 years ago
Massive cultivation in the Loess Plateau
Sanmenxia Reservoir
−0.024 Gt yr−2
Grain for Green Program and Unified Basin Regulation
Xiaolangdi Reservoir
0.148 Gt yr−1
B.C. A.D.
Year
b Sediment concentrations
Sediment concentration (kg m−3)
Period average value
1961–1975
1976–1990
1991–2005
2006–2020
Period
c Spatial pattern in water and sediment discharge
II Lanzhou
III Toudaoguai
Subcatchment boundary
The Loess Plateau
Rivers
Xiaolangdi reservoir
VI Lijin
Sanmenxia reservoir
I Tangnaihai
IV Tongguan
V Huayuankou
Annual discharge (10⁸ m³ yr−1)
Sediment load (Gt yr−1)
Year
d Responses to temporal variations in sediment flux
Estuary diversion
First water–sediment regulation scheme
Net sediment load (Gt yr−1)
Deposition
Channel erosion
Bankfull discharge
Channel migration rate
Delta area variation
Bankfull discharge (10⁴ m³ s−1)
Channel migration rate
Delta area variation (km²)
Year

Fig. 3 | Spatial and temporal patterns of sediment transport. a, A time series of sediment load in the lower reaches of the Yellow River throughout history (yellow solid line highlights the trends; the data are from refs. 5,77) and from the 1950s to the present day (the solid line and shaded region indicate the linear regression and 95% confidence interval, respectively, with the solid line (right) indicating the periodic mean of the sediment load) in the context of key events. **b**, A box and whisker plot of changes in sediment concentration in the lower reaches of the Yellow River (centre line, the top and bottom of the box and whisker extent indicate the average value, 75% and 25% quantiles and maximum and minimum value in each period, respectively). **c**, Variation and spatial pattern in water (left side of inset plots) and sediment discharge (right side of inset plots) across the source (I), upper (II, III), middle (IV, V) and lower reaches (VI) of the Yellow River Basin (YRB). **d**, Temporal response of the bankfull discharge, (blue bars, the data are derived from ref. 98 and the Yellow River Conservancy Commission), delta area (yellow dots, the data are from refs. 95,103,104,209,210) and channel migration rate (blue dots) of the lower Yellow River in response to temporal variations in sediment flux (colour bar (top), the data are from ref. 89). The blue and yellow solid lines and shaded areas show the regression line of the generalized linear model and the 95% confidence interval for the channel migration rate and delta area variation, respectively. The data are sourced from the Yellow River Conservancy Commission (Supplementary Table 1) unless otherwise stated. The once-heightened sediment load of the Yellow River has decreased spatially and temporally, leading to changes in the downstream channel and delta.

biodiversity, various wildlife habitats and important over-wintering and breeding sites for migrating birds[94,95]. However, the stability of the Yellow River Delta is heavily influenced by changes in the dynamics of the sediment load[95].

Responses to decreased sediment

Decreased sediment flux, as well as active reservoir regulation, have mitigated the problem of sediment deposition in the lower reaches of the Yellow River. Upstream regulation, including landscape engineering, ecological restoration and reservoir operation in the late twentieth century[89,96], led to a continuous decrease in the sediment load, reducing the deposition rate in the lower reaches[86]. In 2000, the sediment load entering the lower reaches of the Yellow River dropped below 0.1 Gt yr^{-1}, leading to a transition from a state of deposition to net erosion[86]. Furthermore, the Water–Sediment Regulation Scheme implemented after 2002 has accelerated the incision and widening of the channel[86,96]. Consequently, the elevation of the riverbed has decreased by up to 3 m (refs. 96,97), the bankfull discharge (the maximum discharge that can be held within the channel) of the lower Yellow River increased by 200% (ref. 98), and the river channel has stabilized[89] (Fig. 3d and Supplementary Fig. 4). These changes have benefited flood control in the lower reaches of the Yellow River, enabling further agricultural development on the floodplain[89]. Whether this reduced sediment load can be sustained remains a critical challenge for communities within the YRB.

Nevertheless, the evolution of reservoirs and the riverbed in the lower reaches has posed challenges to the sustainability of strategies for the mitigation of sediment deposition and flooding. For example, the Sanmenxia and Xiaolangdi reservoirs, which were built to control water and sediment flux in the lower reaches of the Yellow River in 1961 and 1999, respectively, have undergone severe siltation[99,100]. Consequently, their storage capacity and the flushing efficiency in the lower reaches have reduced[86,99,101]. In addition, channel erosion downstream of the dams has led to riverbed incision and coarsening of the bed sediment, because fine sediment is preferentially entrained in water flow[99,100]. This bed coarsening makes the riverbed more difficult to erode[99]. Furthermore, a coarsened riverbed leads to the formation of larger sand dunes in the channel, which increases flow drag. Such extra drag has been proposed to exacerbate the risk of flooding during moderate and large floods[97,102].

Reductions in sedimentation also have negative impacts on the Yellow River Delta, with delta expansion slowing since the 1990s[79,95,103,104] (Fig. 3d and Supplementary Fig. 4). Despite delta growth continuing near the estuary, coastal erosion has occurred further away from the estuary[79,103], leading to concerns over potential ecological degradation resulting from delta shrinkage[79,104,105]. In addition, the delta is vulnerable to the effects of climate change such as sea level rise[106]; therefore, approaches to sediment regulation in the YRB must balance the need for flood protection in the lower reaches with the sustainability of the delta.

Anthropogenic changes

Population growth, urbanization and human activities have shaped the socio-ecological landscape of the YRB since the 1950s. This section explores the complex human dimensions driving changes within the YRB, including demographic shifts, patterns of water use, land use transformations and socioeconomic developments.

Changing population distribution

Population expansion and increased demands for food and energy have intensified water stresses in the YRB. The human population in the YRB rose from 10 million in the seventh century to 100 million in 1950, 146 million in 1980 and 216 million in 2020 (Fig. 4a, Supplementary Table 1). Urbanization and population aging have led to shifts in lifestyle, consumption and production patterns, altering water use in various sectors and producing other environmental impacts[107] (Fig. 4b). Rapid industrialization and urbanization correlate with population increase over the same periods[108] (Fig. 4a). Despite the continuous population growth from 1980 to 2020, the per capita water withdrawal in the middle and lower reaches of the YRB declined from 396 m^3 yr^{-1} in 1980 to 310 m^3 yr^{-1} in 2020, partly owing to stricter water resource management and transformations in production patterns. These changes highlight a pronounced spatial mismatch between water resource endowments and population distributions (Fig. 4). Moreover, water scarcity is further intensified by the prevalent migration of people towards economically developed downstream regions that are already experiencing water stress[109–111].

Changes in water use

Water use in the YRB faces substantial pressures related to population growth, urbanization and economic activities. Water demand has increased by 15.8% since the 1980s (Fig. 4c). Between 1980 and 1997, water use increased at a rate of 1.02 km^3 yr^{-2}, mainly for irrigation, leading to a 63.7% (ref. 112, during 1982–2014) decrease in the discharge of the Yellow River[112–115]. Industrial water use, the second largest sector, increased by 17.43% between 1980 and 2020. However, the rate of increase of industrial water use began to decline after 2000, changing from 0.28 km^3 yr^{-2} before 1997 to −0.02 km^3 yr^{-2} after 2000. Domestic water use, corresponding to water withdrawal for urban and rural household use and service activities, increased steadily at a rate of 0.17 km^3 yr^{-2} from 1980 to 2020, owing to population growth,

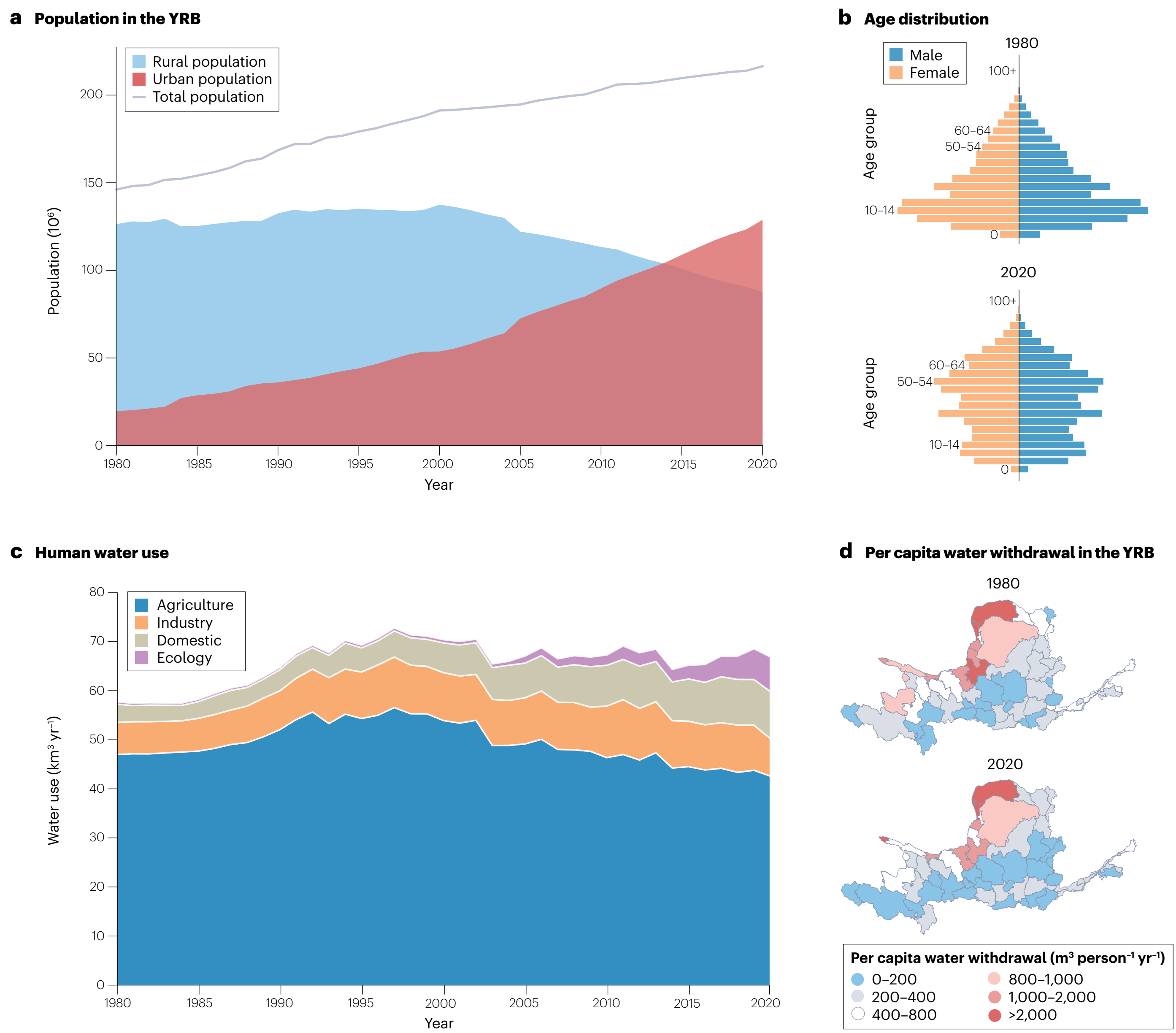

Fig. 4 | Population and human water use. a, Changes in the rural, urban and total population in the Yellow River Basin (YRB) (the data are from City Statistical Yearbook and the National Census of China) (Supplementary Table 1). **b**, The distribution of the YRB population in 1980 and 2020 (the data are from City Statistical Yearbook and the National Census of China) (Supplementary Table 1). **c**, The contribution of agricultural, industrial, domestic and ecology sectors to human water use in the YRB (the data are from Provincial Water Resource Bulletins (2000–2020); Nation Long-term Water Use Dataset of China (1965–2013)[211] (Supplementary Table 1). **d**, Spatial distribution of per capita water withdrawal in the YRB in 1980 and 2020 (the data are calculated from human water use data and population data) (Supplementary Table 1). The changes in the population of the YRB and economic importance of each industry between 1980 and 2020 have driven changes in water use across multiple sectors.

especially in urban areas. Consequently, the contribution of domestic water use to total water use increased from 6.5% in 1980 to 14.3% in 2020. Ecological water use, referring to the water used to maintain ecosystems (including sediment flushing, planting trees and grass, recharging rivers and restoring dried-up regions), has expanded rapidly since the 2000s (0.31 $km^3\ yr^{-2}$), owing to efforts to introduce policies to support sustainability of the river ecosystem[116].

Although water management practices have decreased per capita water withdrawal since the 1980s, there is still a substantial disparity between water availability and demand. Severe drying-up of the river occurred during 1980s–2000s; consequently, approaches such as the Water Allocation Scheme (1998)[117] and the construction of the Xiaolangdi Reservoir in 1999, were proposed to mitigate water scarcity[12,118,119]. These approaches led to a downward trend in water use (−0.715 km^3 yr^{-2}) before 2000. This trend stabilized after 2004 (−0.02 km^3 yr^{-2}), being balanced by high human demand. The structure of water use has changed concurrently in response to these economic and social demand shifts. For example, the contribution of agricultural water use decreased from 81.44% to 63.75% between 1980 and 2020 but remains much higher than other sectors (Fig. 4c and Supplementary Fig. 5). Despite these measures, human water withdrawal still reached 84% of the available surface water resources in 2020, breaching the 40% water scarcity threshold[120]. Per capita water availability was still only 473 m^3 yr^{-1} (ref. 121) until 2020, representing ~23% of the national average in China, and falling well below the global threshold for severe water scarcity (500 m^3 yr^{-1}) (Fig. 4d).

Land use and vegetation changes

Cultivation, over-grazing and human interventions have caused ecological degradation in the YRB. This degradation started in the eleventh century, accelerated in the eighteenth century[18,40,70,122] and persisted until the 1990s[18,123]. By 1850, anthropogenic land use exceeded natural land cover in 43% of the Loess Plateau (Fig. 5a). From 1950 to 1960, the extent of cropland on the Loess Plateau increased by 5 × 10^6 ha, further reducing natural vegetation coverage[70,124]. In the source region, grassland shrinkage, degradation, and desertification have been continuous since the 1970s[10,125]; consequently, vegetation cover decreased in 67% of the source region between 1982 and 2001[126]. This severe degradation could lead to increased soil erosion, increased sediment flux into the Yellow River and, consequently, intensified channel diversion[127].

In the frozen regions of the YRB, anthropogenic warming will alter sediment flux and vegetation growth. Enhanced melting of permafrost areas in the source regions of the Yellow River on the Tibetan Plateau has increased sediment flux and channel mobility[127]. Conversely, the effect of increasing temperatures in warmer areas with seasonally

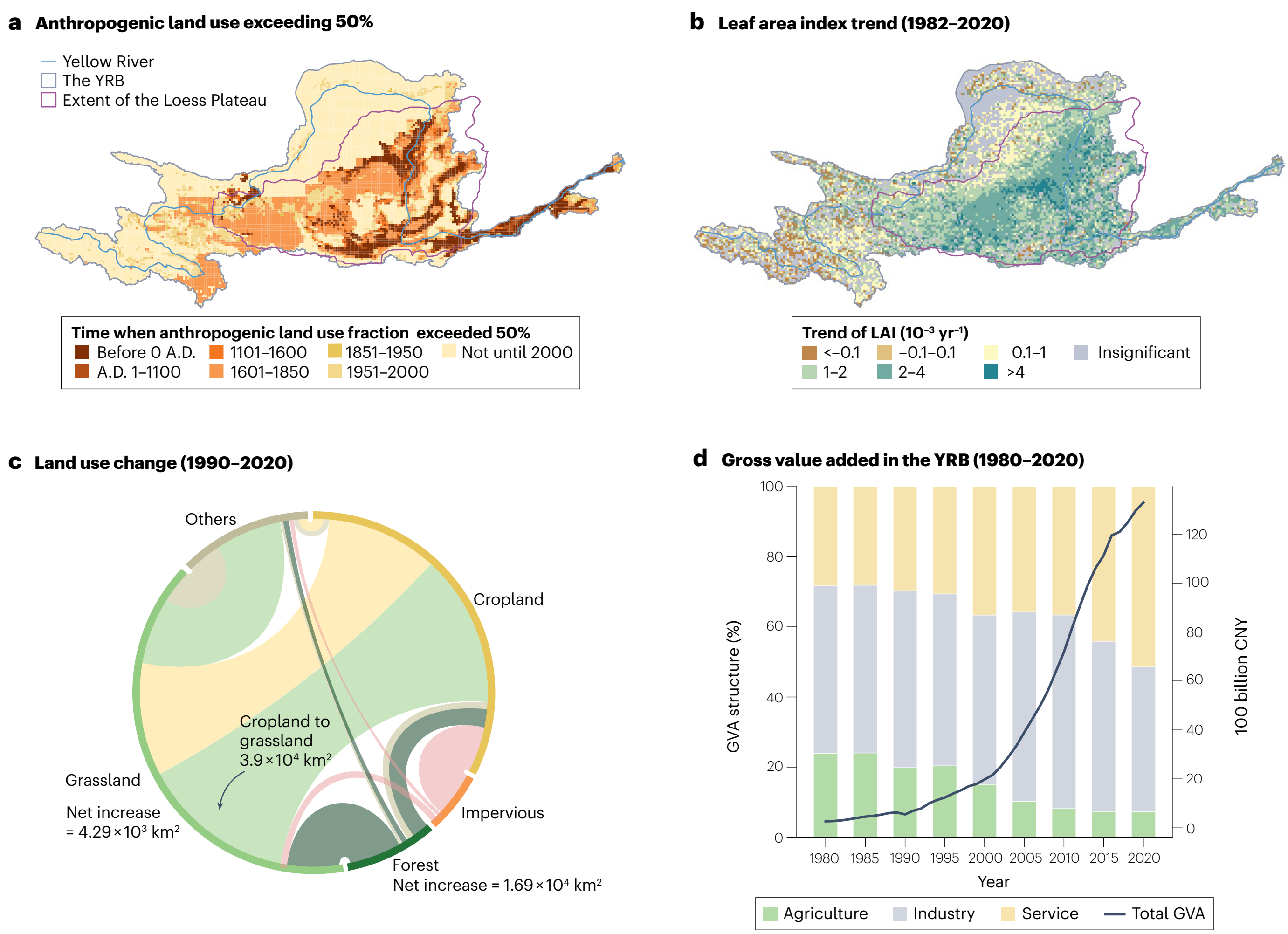

Fig. 5 | Land use, vegetation and economic changes. a, Spatial distribution of the years when the proportion of anthropogenic land use exceeded 50% in the Yellow River Basin (YRB) (the data are from HYDE 3.3 (ref. 212)). **b**, Trend in leaf area index (LAI) between 1982 and 2020 (data from GIMMS LAI4g[213]). **c**, A chord diagram of land use change in the YRB between 1990 and 2020 (the data are from CLCD[214], the thickness of the chords represents the area of land use change with the chord colour representing the new land use). **d**, The total gross value added (GVA) (solid line) and contribution of agriculture, industry and service to the GVA (coloured bars) in the YRB (1980–2020) (the data are from City Statistical Yearbook and the National Census of China) (Supplementary Table 1). Since the 1980s, the YRB has experienced rapid economic growth and ecological restoration efforts have increased vegetation coverage. CNY, Chinese Yuan.

frozen ground is modulated by enhanced vegetation growth, which stabilizes river banks and reduces channel migration[127].

Various landscape engineering approaches have been implemented to control soil erosion and reduce sediment flux into the Yellow River. The construction of check dams, which intercept sediment on hillsides or in valleys, was promoted and implemented in the 1950s; by 2011, there were over 58,000 check dams in the YRB[128,129]. Moreover, terrace farming was promoted in the middle reaches of the Yellow River[16,70,130] with the extent of terraces reaching 6.46×10^4 km^2 by 2022 (ref. 131). These measures reduced sediment flux into the Yellow River in addition to ensuring that agricultural productivity was maintained to sustain a growing population[70,129,132]. However, there is a limit on the ability of landscape engineering to reduce sediment yield[16,128]. For instance, check dams can silt up and lose their retention capacity within 10 years owing to high sediment production[128].

Various ecological and conservation projects have been implemented in the YRB, leading to increased vegetation coverage, which mitigates soil erosion. Such projects began in the 1980s and emerged rapidly throughout the late twentieth century, including the Three North Shelterbelt Forest Program (1978)[8,123,133], which promoted afforestation, the Natural Forest Protection Program (1998)[8,123,134,135], which aimed to prevent deforestation, and the Grain for Green Program (1999)[8,123,135,136], which supported the conversion of cropland to forest or grassland. These projects have enhanced forest and grassland vegetation substantially in the YRB[8,123,135,137] (Fig. 5b,c). Between 1982 and 2020, 71% of the YRB experienced a significant ($P < 0.05$) increase in leaf area index (Fig. 5b). In addition, the area of grassland and forest increased by 4.29×10^3 km^2 (1.0%) and 1.69×10^4 km^2 (22.8%), respectively, between 1990 and 2020 (Fig. 5c), and the fractional vegetation cover increased by 17% between the years 1999 and 2018[138]. The normalized difference vegetation index increased in over 60% of the area in the source region during the 2000s, as barren land was converted to grassland[139,140]. In addition, in the Loess Plateau, vegetation coverage increased from 31.6% in 1999 to 59.6% in 2013, reaching 65% in 2021 owing to the conversion of cropland to grasslands and forests[11,16,141–143] (Supplementary Fig. 2).

Economics and policies

Since 1980, the YRB has experienced rapid economic growth, placing increasing demands on water resources. The gross value added (GVA) of the YRB increased by an average of 1.78% per year between 1980 and 2020 (Fig. 5d). In this period, the contribution of agriculture to the total GVA in the YRB decreased from 24.5% to 7.5%, the share of service GVA rose from 27.6% to 51.4%, and the industrial share decreased from 47.9% to 41.3% (Fig. 5d and Supplementary Fig. 5). Along with these changes, the efficiency of industrial water use increased[144,145], high water-consuming and energy-consuming industries were replaced[146], and infrastructure was enhanced to promote water-saving technology and establish standard water quotas across sectors[147].

As water resources become the primary factor restricting economic growth, water-related policies have been proposed to govern the YRB. Before the 1980s, initiatives concentrated primarily on the use of large-scale engineering projects, such as reservoirs and levees, to meet the increasing demands for agricultural, industrial and domestic water and to control floods. For example, the Sanmenxia and Liujiaxia Dams were constructed to control floods and generate hydropower. Since 1980, the focus has shifted to comprehensive institutional governance[19] (Supplementary Fig. 6). For instance, the Water Allocation Scheme (1987)[148] was the first unified plan to allocate Yellow River water across provinces, laying the foundation for coordinated basin management. Although the goal of halting growth in water usage was not achieved in the first decade, the withdrawal of water was strictly regulated as the administrative authority of the Yellow River Conservancy Commission expanded. In 2010, the Yellow River Conservancy Commission won the Lee Kuan Yew Water Prize[149] for its complex management system[9,20], which prevented the Yellow River from drying up. The construction of the Xiaolangdi Reservoir in 1999 strengthened integrated water management through its multifunction purpose of flood control, water and sediment regulation and maintaining ecological basic flows[105,150,151].

After the peak in water use in 1997, enhanced water quota policies, including the Water Allocation Scheme (1998)[117], were introduced to further strengthen unified water management from the supply side. Policies to transfer water rights and reform agricultural water prices were also implemented from the demand side[152,153] (Supplementary Fig. 6). The aim was to give agrarian water rights to the industrial sector in exchange for fees to develop water infrastructure[154]. From the 2010s to the 2020s, several technique-guided policies, such as Integrated Fertilizers and Water Use Management in Agriculture[155], were released to promote water-saving irrigation technologies (Supplementary Fig. 6). With additional further infrastructure and policies, such as Water Diversion from South to North[156], Strict Water Management[157] and the Yellow River Protection Law (2022)[158], efficient use of water resources has become a performance indicator for local administrative officials.

Interplay of human and hydrological systems

Anthropogenic impacts have reshaped the hydrological dynamics of the YRB and, over time, led to further feedbacks for society. Population growth and agricultural expansion have affected the YRB for thousands of years, resulting in the removal of vegetation, severe soil erosion, and increased sediment loads[17]. Since the 1960s, anthropogenic activities have intensified owing to a growing population and food demands. Modernization and industrialization have stimulated engineering projects, such as reservoir construction, which alter water flow and sediment transport. Meanwhile, ecological restoration projects have altered vegetation patterns and reduced water and sediment loads. This section examines the feedback mechanisms between anthropogenic interventions and hydrological changes, identifying four hypothetical feedback loops (Fig. 6) and suggesting potential future changes. Detailed institutional and engineering solutions, plans and future potential changes are given in Supplementary Fig. 6 and Supplementary Table 3.

Feedback loops

Challenges have emerged from the ongoing intertwined interactions between humans and water, with uncertainties arising from institutional, social and technical transitions and climatic changes[159–161]. Over different periods, the strength and influence of these drivers have varied substantially, leading to complex feedback loops that govern the interactions between human activities and the natural environment. These shifts have caused ecological and hydrological transformations, which have often reinforced each other and complicated efforts to balance environmental protection with economic and social development in the YRB.

The supply expansion feedback loop during 1960–1980 was characterised by expanding water supply programmes to meet social and economic development demands, which reduced water discharge[19] (Fig. 6a). Rapid socioeconomic development (for example, the GVA) in this arid and semi-arid region relies heavily on water resources[162].

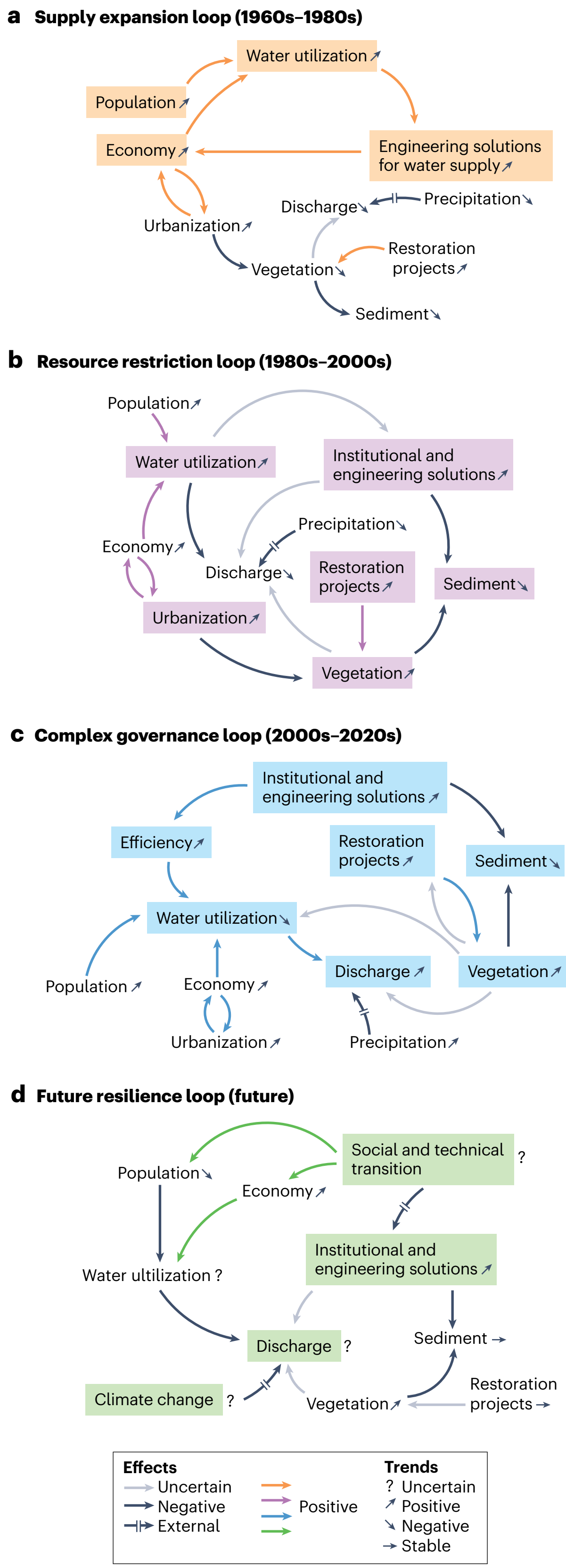

Fig. 6 | Feedback loops for anthropogenic impacts on the Yellow River. **a**, Supply expansion loop (1960s–1980s), characterized by the growth of water supply programmes to meet the demands of social and economic development. The coloured boxes indicate dominant loops. **b**, A resource restriction loop (1980s–2000s) involving strategies to restrict water demand and the initial implementation of ecological restoration projects. **c**, A complex governance loop (2000s–2020 s) in which institutional and engineering solutions increased water use efficiency, enhanced vegetation and reduced sediment yield. **d**, A future resilience loop characterized by uncertainties from climate change and socioeconomic development. The four hypothetical feedback loops represent dynamic interactions between human and water system components across different periods.

Therefore, engineering infrastructure, such as diversion projects, were developed to boost water supply. This water supply supported further economic activities, creating an accelerating feedback loop. The increasing demand, driven by engineering-intensive development, led to the appropriation of water resources from external regions and other stakeholders within the basin[163,164]. The lack of adequate policies and institutional constraints led to further scrambles for water allocation and drying-up crises for streamflow[165]. Moreover, urbanization and land development restrict vegetation cover, further impacting discharge and sediment flux[19,124].

Between 1980 and 2000, water scarcity became a key driver of institutional shifts in the YRB leading to strategies to restrict water demand[20]. Population growth, economic development and urbanization continued to drive demand (for example, food and energy). Therefore, water scarcity curbed uncontrolled exploitation through institutional reforms and monetary policies. However, mismatched institutional structures, under which the provinces engage in uncoordinated competition for scarce water owing to economic growth pressures, led to intensified exploitation of water resources, fuelling disputes over the fairness of governance outcomes[166,167] (Fig. 6b). In the late 1990s, ecological restoration efforts began to emerge to mitigate some of the adverse effects (such as, drying up[113], wetland shrinkage[94] and increasing soil salinization[168]) of past practices[169].

A complex governance loop emerged throughout 2000–2020 in which water use efficiency increased via demand-side and supply-side management[118] and strategies such as water diversions and ecological projects were introduced to enhance vegetation and reduce sediment yield[16]. Increased diversity in policy and governance enhanced water use efficiency[118], reducing overall water consumption (Fig. 6c). Meanwhile, ecological conservation and restoration efforts began to control soil erosion more effectively with unified regulation also enhancing the management of sediment deposition. Large-scale vegetation conservation and landscape engineering projects were also implemented to control severe soil erosion in the YRB.

However, vegetation restoration projects also altered hydrological processes (Fig. 6c). For example, the rapid increase in vegetation has increased evapotranspiration, reduced runoff and discharge, and caused soil moisture depletion[26,50,170]. By 2021, vegetation in the eroded sediment areas of the middle reaches of the Yellow River had nearly recovered to its ecological threshold level (65%)[142]. Downstream water discharge dropped by 38% from 1971–1990 to 1991–2016, with vegetation increase responsible for up to 26% of this decline[16,25,171]. The depletion of soil moisture and terrestrial water storage has raised concerns about hydrological sustainability in the YRB. In 2008, the maximum depth of the dried soil layer reached 5 m, primarily in the forest regions[26,50,172,173]. This depletion limits the future effects of ecological restoration and threatens water resource availability in the middle and lower reaches of the Yellow River[11,174,175]. Therefore, instead of extensive afforestation, mixtures of trees, shrubs and herbaceous plants adapted to local conditions should be prioritized to balance hydrological sustainability and ecological effectiveness[13]. It is also possible that increased vegetation could enhance local water cycles and increase precipitation; however, the degree and importance of this feedback are uncertain[39,74,75].

Future changes

Climate change is expected to alter future water availability (Fig. 6d). Engineering and institutional approaches to address soil erosion and excessive water withdrawals have curbed the overall deterioration in water resources. However, dependence on more extensive human interventions has resulted in a legacy of maximizing water resource utilization[19]. The increasing frequency and severity of extreme events under the impacts of climate change might diminish the stability of water supply and challenge this water management system, which was optimized under previous human–river relationships. Glacial melting[176] will also lead to the loss of stored water. Future water resources in the YRB are projected to increase by 0.218 ± 0.201 km^3 yr^{-1} under various climate change scenarios and models (Supplementary Fig. 6). These perceived improvements in water availability could lead to increased dependence on external factors, such as increasing precipitation. Underestimating the risks associated with water crises could weaken the motivation for proactive management and policy interventions in the short term. Given that institutional reforms often exhibit inherent delays, there might be further water depletion in the long term[177], increasing the vulnerability of the system.

The compound impacts of reduced cropland area, population decrease[178] and improvements in the efficiency of water use are projected to mitigate human water demand in the late twenty-first century (Fig. 6d). Models incorporating fertility policies, well-being and economic growth project that the population of the YRB will peak around 2020–2030 (Supplementary Fig. 6). However, an ageing population might lead to more uncertain behaviours in water use (Supplementary Fig. 5). Ongoing demographic change, production shifts and climate change are likely to cause a decline in cropland area until the 2100s, leading to reduced agricultural water demand. In addition, socioeconomic and technological transitions have led to improvements in the efficiency of water use. Human water demand, modelled by integrating complex system transitions — including future population changes, land use changes, economic cycle fluctuations[179], technological changes and shifts in human lifestyle[180] — will potentially reach a peak of 74 km^3 yr^{-1} in the mid-twenty-first century, still exceeding the 2020 level of 67 km^3 yr^{-1}.

Other projected changes, such as urbanization, forest and grassland expansion and increased ecological water use, could increase water demand for humans and the broader ecosystem. Urbanization is expected to continue to increase and is projected to reach 75–90% by the 2100s (Supplementary Fig. 6), accelerating the increase in domestic, food and industrial water use. The expansion of forests and grasslands remains possible under different scenarios, driven by ongoing ecological restoration efforts and climate change (Supplementary Fig. 6). This potential increase in vegetation could pose risks to domestic, industrial, and irrigated water availability. Moreover, the share of ecological water use (for example, to supplement wetland, groundwater and urban greenspace) is predicted to grow and compete with human water use for social and economic activities[12] and threaten food production[181]. High water stress in the YRB will persist unless there is a shift in the demand[109,181].

Complex anthropogenic–hydrological feedbacks must be considered when negotiating the conflict between human demands and water. Approaches such as landscape engineering, reservoir operation and ecological restoration have been used to address the problem of sedimentation in the YRB[16]. However, inertia in resource allocation might result in diminishing marginal returns and a reduced ability to respond to emerging risks. Challenges such as reaching engineering saturation, soil moisture depletion and limitations on water resources can seriously compromise the efficiency of these sediment reduction strategies[11,128,174]. Therefore, it is important to design feedback loops to be more adaptive when facing such uncertain and complex risks.

Summary and future perspectives

Despite being historically the world's most sediment-laden major river, the YRB is now experiencing a simultaneous decline in water discharge, soil moisture and groundwater alongside rising human water consumption and evapotranspiration. Consequently, the overall flux of the water cycle is intensifying, whereas water resource storage is diminishing. Since the mid-twentieth century, large-scale engineering works and policy reforms have reduced sediment loads. Compounded by drivers such as land use transformation, escalating urbanization, and evolving water usage patterns, these projects have also altered eco-hydrological processes. The complex interplay of hydrological change, human intervention and institutional policies in the YRB exemplifies a new, multifaceted era in arid river basin management: this era is characterized by short-term water supply successes but heightened long-term risks, such as groundwater depletion and mounting agricultural dependence on irrigation. These risks foreshadow a potential water crisis that, when combined with future climate pressures, underscores the need for transformative and adaptive water governance in the YRB.

Several unresolved challenges remain for the YRB that require further hydrological research, and are issues shared by major river basins globally. First, the complexities surrounding how vegetation restoration regulates river systems, especially its feedback with precipitation, remain poorly understood but could have important implications for arid rivers undergoing restoration or deforestation, such as the Tarim[176], Congo watershed[182] and Amazon rivers[183,184]. Second, managing the delicate balance between controlling soil erosion and safeguarding increasingly urbanized delta ecosystems introduces scientific and policy dilemmas, as seen in major deltas[185], such as those of the Mekong[186], Rhine[187] and Yangtze[188] rivers. Third, the unintended consequences of water management policies[167] — such as shifting stress from surface to groundwater resources — raise questions concerning the sustainability of interventions across transboundary rivers[189], including the Colorado, Murray and Orange rivers[190]. Thus, further research on the YRB is important for investigating globally relevant eco-hydrological challenges and developing innovative, transferable solutions.

Comprehensive monitoring is needed to better understand arid-region river systems such as the YRB[3,8,191]. Monitoring in the YRB focuses primarily on flux measurements, such as water and sediment discharge, and evapotranspiration for water resource management. There is a shortage of dynamic monitoring data of water storage in groundwater, soil moisture and glaciers. Measurements of these water storage components rely on coarse estimations using large-scale models or remote sensing methods. The long-term decline in water storage across the YRB could lead to water resource crises that might be overlooked by traditional monitoring flux metrics[192,193]. Thus, comprehensive monitoring networks are needed to capture dynamic variables of the water cycle, develop a digital twin of the river system based on real-world data and consider the economic and technical feasibility of different policies and forecasts[194]. Such monitoring and simulation technologies have been widely used in water resource management in urban areas to improve water use efficiency. However, data are still lacking in sparsely populated, underdeveloped regions. Addressing these data limitations will enable integrated modelling of human–water systems and water management within the river basin[195].

Adaptive capacity in regional water management practices is necessary to bridge the gap between science and policy, facilitating responses to immediate challenges and long-term uncertainties in a changing climate and socioeconomic context. The unexpected outcomes of water management policies, such as the water quota policy[20], reveal the complexity of river basins. Theoretical and practical gaps in the pliability of scientific research and policy-making can lead to long-term legacy effects, despite achieving success in addressing immediate challenges. The lag between intervention and impact can span decades, resulting in inequality in access to water resources among various stakeholders across different periods and regions[2]. Efforts to enhance adaptive capacity must balance the competing objectives of economic development, ecological preservation and social equity[1]. For instance, future work should aim to explore the carrying capacity of water resources; reducing human interference; prioritizing nature-based solutions; the benefits of adaptive policies such as water rights trade, adapting forestry, shrubs and grassland to environmental conditions; and reforming rigid institutions[1,196].

It is essential that scientific knowledge from different regions and cooperation across areas is used to achieve adaptive water governance[189]. Therefore, sustained investment in interdisciplinary collaborative platforms, including funding, the development of young scientists, international partnership networks, and standardized assessment indicators is needed to integrate the strengths of all parties and bridge the knowledge gap in sustainable river management.

Data availability

Supplementary Table 1 outlines details of the datasets used in Figs. 1–4.

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Author contributions

S.W., S.S. and B.F. formulated the review and identified the themes to be covered. S.S., H.Z., L.Y. and C.J. drafted the figures and wrote the first draft of the manuscript. P.R. helped structure and revise the manuscript; J.B., X.W., C.L. and W.Z. revised the manuscript and provided extensive comments. All authors made substantial contributions to the discussion of content.

Competing interests

The authors declare no competing interests.

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