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Perspectives on emerging pressures and their integrated impact on large river systems: An insight from the Yellow River basin

Durgesh Kumar Singh [a], Mengzhen Xu [a,*], Nandita Singh [b], Fakai Lei [a]

[a] River Research Institute, Department of Hydraulic Engineering, Tsinghua University, Beijing, PR China
[b] School of Natural Sciences, Technology and Environmental Studies, Södertörn University, Stockholm, Sweden

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ABSTRACT

The Yellow River, with a developmental and historical significance to China, is now facing several emerging pressures, which are degrading the river status and creating challenges for high-quality development in the basin. Numerous studies on such emerging pressures, present scattered outcomes, and trigger uncertainties and deficient assumptions on the river's problems. This review integrated such scattered information and investigated the emerging pressures, their drivers and integrated impacts at the basin level. The study intended to prioritize those pressures needing expeditious consideration, and carried a discussion on the alternative pathways to the solution. To determine the critical emerging pressures, a literature review was conducted and experts' opinion was sought. The outcome further led to a comprehensive review, data collection, and analysis of three groups of emerging pressures.

The review recognized 'Water Stress' in the lower reach, primarily caused by an abated flow, as the most distressing emerging pressure inflicting social, ecological, and economic consequences. Such decline in flow was mostly induced by a recent increase in 'Anthropogenic activities', such as intensive water withdrawal for irrigation (≥27 BCM), and construction of check dams in the Loess Plateau region (trapping~5 BCM water). The increasing 'Pollution' in the river, besides threatening public health and ecology, also contributed to the water stress by rendering certain stretches of the river biologically dead and unsuitable for any use. The 'Climate Change', with its key negative effect on precipitation in the middle sub-basin, overall contributed small (8–11 %) to the observed reduction in river flow. With increasing challenges for the adopted engineering solutions tackling the water stress, the study suggested the use of a demand management approach, employing adaptive policy measures, as an alternative or supplementary solution to the current approach. In addition, the study highlights that regular reviewing and reforming the key decisions based on evidence and updated information, and taking a participatory approach, may offer a sustainable pathway to the environment as well as socio-economic goals.

1. Introduction

Rivers are globally exposed to multiple pressures, which are degrading their water quality, quantity, ecological status, and ecosystem functions (Capitão and Romero, 2015; Elosegi et al., 2019; Grizzetti et al., 2017; Hering et al., 2015). The pressures on rivers are the means by which drivers (economic, social, technological, etc.) modify the state of rivers (Cooper, 2012). To reduce such pressures, and to effectively improve rivers condition, the holistic basin approaches, such as Integrated River Basin Management and Integrated Water Resources Management, were introduced in the past. They emphasized on recognizing and coordinating the interest of competing stakeholders and sectors to sustainably manage the water resources and the socio-economic development in the basin (Harsha, 2012). The basin planning was adopted by developing countries such as India and China quite early, but the operational realities were limited to creating engineering solutions and infrastructure development (dams, flood measures, etc.) (Pegram et al., 2013). The rivers in these countries were mostly managed in a dispersed and uncoordinated manner, often focusing on regional interests (Harsha, 2012; Zuo and Liu, 2015). Such management practices, often lacking an integrated approach on multiple pressures at the basin level, lead to exaggerated consequences on river systems. With further

* Corresponding author.
E-mail addresses: durgeshsinghus@yahoo.com (D.K. Singh), mzxu@mail.tsinghua.edu.cn (M. Xu), nandita.singh@sh.se (N. Singh), leifk17@mails.tsinghua.edu.cn (F. Lei).

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emergence of new pressures in the last few decades, such as climate change, rapid urbanization, land-use change, pollution, etc., the impacts have become severe, complex, and far-reaching.

Yellow River, the second largest river of China, with 420 million people inhabiting its basin, is having a high developmental and historical significance for the country (Shi et al., 2020). Historically, the management of this river represents a significant example from China where the focus remained on few issues, such as floods, irrigation, soil erosion and sediment management (Fig. 1) (Giordano et al., 2004; Mei and Dregne, 2001; Wu et al., 2004). In past, separate interventions were introduced to treat these issues in isolation, which caused serious modifications in the river system, eventually inducing a new set of problems.

The river, in the past few decades, has increasingly experienced acute threats from multifarious emerging pressures. In the last two decades, numerous studies thus began highlighting such concerns on land-use change, anthropogenic water withdrawal, climatic factors, etc. (Table A.1). The past studies, however, mostly demonstrated fragmented insight and offered assessments on one or two pressures. These studies largely failed to demonstrate a holistic view on drivers-pressures linkage, the spatial distribution of pressures, and their integrated impacts on the river system. The studies were carried on diverse spatial scales, and even if focused on the same pressures in the same study area, often involved different objectives, methods, and tools (Table A.1). With such research heterogeneity, it is usual to find varying conclusions or contrasting arguments, only to foster confusion and deficient assumptions. Such a situation genuinely confines the ability of decision-makers and researchers to understand the basin problems, and hinders the effective use of a vast pool of information. Previously lacking a thorough review on such scattered findings, a need was felt to enhance insight on such emerging pressures.

The key objectives of this review are:

(1) to recognize and characterize the key emerging pressures and their coupled impacts in the Yellow River basin (YRB).
(2) to explore driver-pressure-impact linkage in the basin, and to highlight sub-basins and sectoral contribution to the pressures.
(3) to prioritize the significant emerging pressures needing expeditious consideration, and to discuss approaches to address such emerging pressures.

The study specifically focused on the pressures that emerged in the last 40 years (since the 1980s), and still affecting the river. The paper avoided discussing the impacts of large reservoirs and dams, as it has already been discussed extensively before.

2. Methods and the study area

2.1. Methods

The emerging pressures on the Yellow River were determined by administrating a preliminary review of the research articles that mostly published after the year 2000. To further confirm the review's findings, an expert's opinion was additionally sought from the researchers and key persons engaged in the Yellow River issues. The findings held the following group of emerging pressures accountable in the Yellow River system: 1) Water Stress, 2) Climate Change, 3) Anthropogenic Activities (quantitative and qualitative impacts).

A comprehensive review was further carried on the identified emerging pressures, using online libraries and reports. The study area was digitized employing ArcGIS tools. Several data, such as basin annual runoff, basin spatial characteristics, river drying days, annual precipitation, land-use change, water consumption, irrigated area etc., were assembled and restructured from secondary sources, and used for analysis. The land-use obtained from different case studies had a dissimilar number of classes. The closely related classes, in each case, were merged to present land-use data in broadly six classes: cropland, forest cover, grassland, water bodies, built-up area, and bare land. For example, 'high grassland', 'medium grassland', and 'low grassland' were merged into one class of 'grassland'.

2.2. The Yellow River and its basin

The Yellow River originates from the Qinghai-Tibetan Plateau and pours into the Bohai Sea. It covers a length of 5464 km and flows through nine provinces of China (Fig. 2). About thirteen main tributaries are flowing into the river. The river and its basin, based on its distinct characteristics, are dissected into three parts: the upper, middle, and lower reach (Fig. 2). The upper sub-basin (USB) mostly comprises mountainous regions. USB has a major runoff yield region, known as the 'source region', which also contains a permafrost area. The source region contributes 38 % of the basin total runoff (Wang et al., 2019b; Zhang et al., 2015). USB has a relatively low population density and limited industrial development. It is also the largest sub-basin and contributes highest runoff to the river, followed by the middle sub-basin (MSB) (Fig. 2). At the beginning of MSB, the river takes a "great bend" and passes through the fragile Loess Plateau, which comprises arid agriculture areas that rely heavily on irrigation. The Loess Plateau is also famously known for its highly erodible loess soil. This eroded soil contributes 90 % of the Yellow River's sediment load (Wang et al., 2007).

The lower sub-basin (LSB) is the smallest among all and comprises flat plains. LSB faces aggradation by the sediment transported from MSB, which makes the river channel here wondering and unstable (Giordano et al., 2004). The river, in the past, had caused several catastrophic floods in the downstream region (comprising parts of MSB and LSB), and thus levees were constructed on the banks of both middle and lower reaches. The river channel in the lower reach, between the levees, constantly received heavy sediment aggradation. It uniquely made the channel elevation here more than 10 m above the surrounding ground (Wu et al., 2004). The increased elevation also modified the basin characteristics, as the surrounding region was unable to drain water into the lower reach (Giordano et al., 2004). LSB thus eventually became the smallest sub-basin.

3. Results and discussion on the emerging pressures

3.1. Water stress

The Yellow River, between 1956 and 2016, had an average natural yield of 53.3 billion cubic meters (BCM) water, with USB, MSB, and LSB contributing 60.3 %, 38.9 %, and 0.8 %, respectively, to the yield (Wang et al., 2019b). In recent decades, the river showed a decline in its mean flow. The mean annual net runoff, from 1951 to 2012, declined at the rate of 0.721 BCM per year, of which 28.4 %, 40.5 %, and 31.1 % of the decline were contributed by USB, MSB, and LSB, respectively (Kong et al., 2016). The situation turned alarming after the lower reach, since 1972, started drying frequently (Li et al., 2004; Liu and Zhang, 2002). Yang et al. (2004) reported that the river, between 1972 and 2000, dried at least 22 times, with little to no flow in certain sections of the lower reach (Fig. 3). Since 1990, the number of days Yellow River dried annually increased (Fig. 3). Simultaneously, the length of dry channel in lower reach also increased (Yang et al., 2004). Such drying conditions led to several social, geomorphological, economic, and ecological consequences for the river and its beneficiaries.

The unavailability of adequate water affected both agriculture and industries to a serious extent. The industries lost approximately 4 billion RMB[1]/yr in the 1990s due to drying conditions in the lower reach (Liu and Zhang, 2002). Similarly, the agriculture losses, in terms of cereal production, amounted to be around 1.3 million tonnes annually,

[1] 1 RMB = 0.15 U.S. Dollar (Approximately).

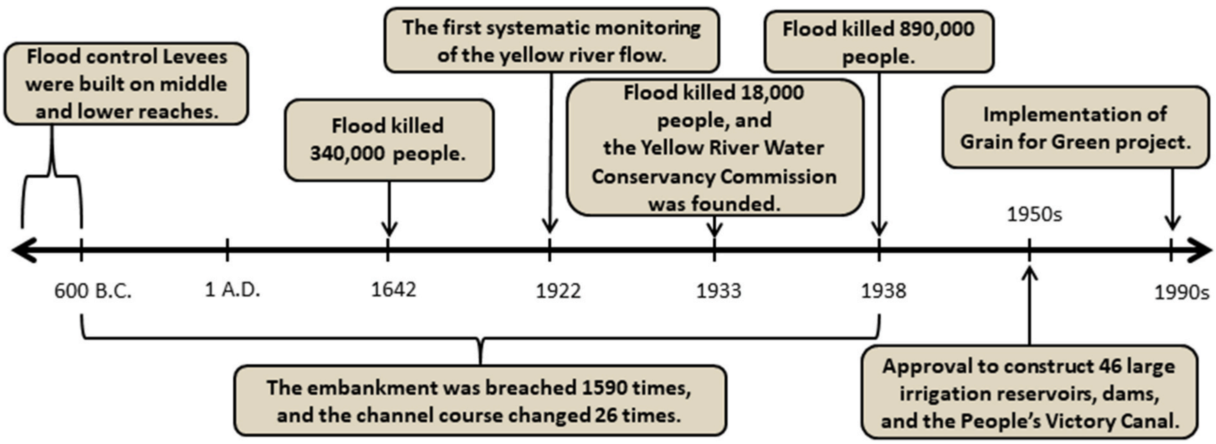

Fig. 1. Timeline of the key events and developments in the Yellow River basin (YRB) (Chen et al., 2007; Giordano et al., 2004; Ongley, 2000; Wu et al., 2004).

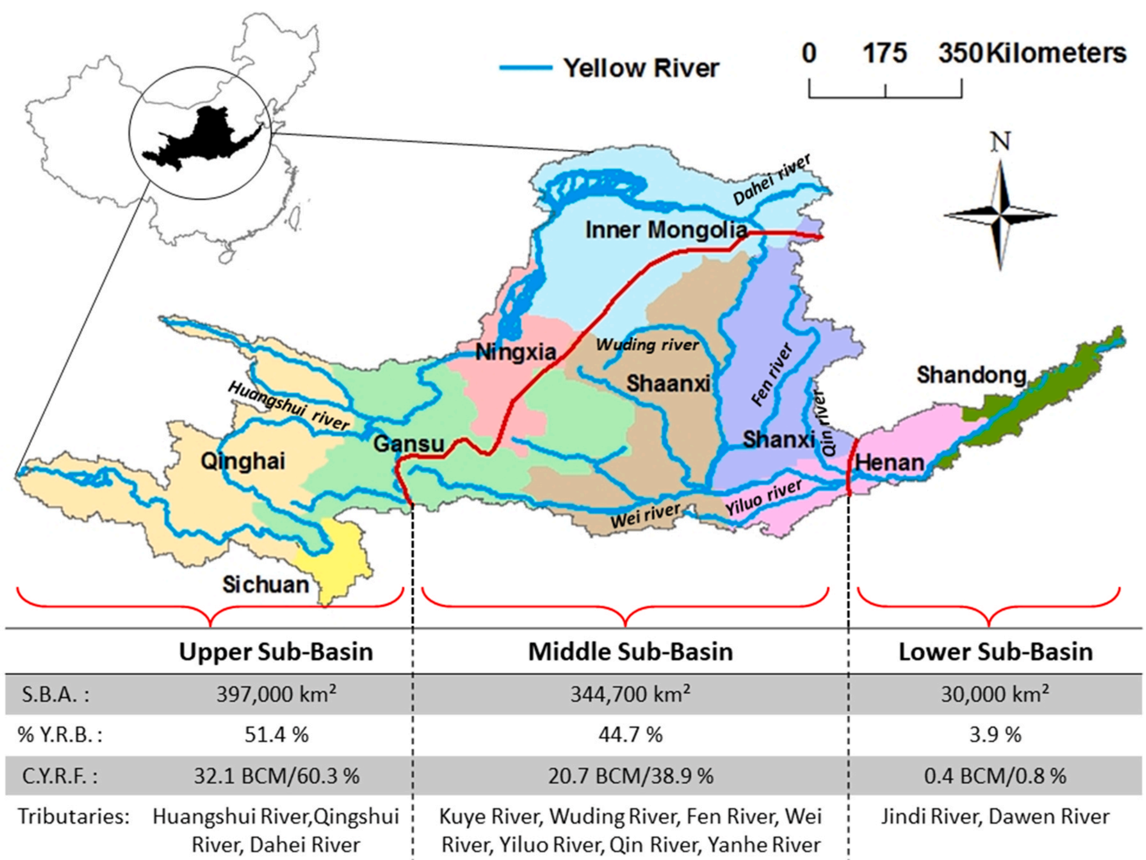

Fig. 2. The spatial representation of the Yellow River, and a comparative account of its sub-basins (Wang et al., 2019b) [S.B.A. = Sub-basin area, %Y.R.B. = Percentage of the total area of YRB, C.Y.R.F. = Mean contribution to the Yellow River annual water yield between 1956 and 2016, colours indicate provincial boundaries]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

resulting in an economic loss of around 1.6 billion RMB (Liu and Zhang, 2002). The river mouth and littoral zone of the Yellow River were regarded as key spawning areas for the fishes, and these regions were extensively used for fish farming (Liu and Zhang, 2002). The water stress endangered such delta and coastal fisheries. Several of the fishes in the river, which used to be an important source of food, became extinct (Karasov, 2002; Reuters, 2007). Declined flow also undermined the river capacity to flush heavy sediments into the sea, resulting in high sediment aggradation in the lower reach and a rise in the river bed (Fu et al., 2004). It can cause a high water level during intense rainfall seasons. Such a situation enlarged the flood vulnerability of the region in case of levee failure, and exerted additional pressure to upgrade the river bank protection (such as higher levees) to avoid massive floods (Liu and Zhang, 2002).

3.2. Climate change

Climate change, in the last few decades, showed negative effects on the Yellow River's flow. According to Miao et al. (2011), climate change was responsible for 45 % of the observed reduction in basin's runoff in the 2000s, with its highest impact in MSB and LSB. The other studies reported that climate change was accountable for merely 8-11 % of the

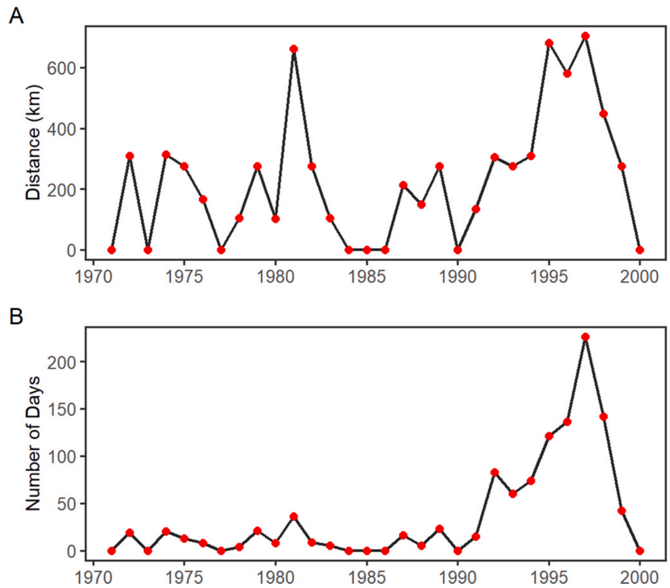

Fig. 3. (A) Length of the dry channel observed annually in the Yellow River, and (B) Numbers of days the Yellow River dried up annually (Yang et al., 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observed decline in basin runoff (Kong et al., 2016; Wang et al., 2012a, 2013). Wang et al. (2012a) suspected the findings of Miao et al. (2011) and suggested that the higher contribution of climate change in their study was caused by the use of runoff data from the gauging stations that were not reflecting the exact runoff change in the section.

The impact of climate change in the source region, an anthropogenically undisturbed region, appeared insignificant owing to a minor change in runoff there (Liu et al., 2008; Shi et al., 2017; Wang et al., 2019b). On the other hand, climate change in the Loess Plateau region of MSB, between 1961 and 2013, contributed 27 % to the total reduction in runoff observed during high flow seasons. Such contribution further enlarged during low flow seasons (Wu et al., 2017a). Such studies highlight climate change as a minor pressure at the basin level but having a varying degree of impacts at the sub-basin levels. Besides knowing the gross contribution of climatic change on runoff, it was desirable to apprehend the contribution of change in temperature and precipitation in the basin. Globally as well as in the case of YRB, the runoff production was regarded as more sensitive to change in precipitation than temperature (Kong et al., 2016; Liang et al., 2015; Shi et al., 2017; Zhang et al., 2007). The upcoming section would probe into the impact of both factors in the basin.

3.2.1. Precipitation

The annual average precipitation, of around 478 mm, showed an uneven distribution in YRB (Chang et al., 2017; Wang et al., 2006). Since the 1950s, the annual precipitation exhibited an insignificant but slightly decreasing trend, mostly in MSB and LSB (Fig. 4) (Chang et al., 2017; Kong et al., 2016; Li et al., 2004; Liu and Cui, 2011; Yang et al., 2004). Even with such a small decline, Wang et al. (2012a) revealed that precipitation was still accountable for 11.8 % of the total reduction observed in basin's run off, with its higher and lower impact in MSB and USB, respectively.

In certain regions of USB, studies even observed a minor increase in annual precipitation, specifically in the source region by approximately 20 mm (Chang et al., 2017; Cuo et al., 2013; Liu and Cui, 2011). However, some lower parts of USB showed a slightly downward trend, but its effect on the runoff was probably offset by a minor increase in other parts of USB (Chang et al., 2017; Liu et al., 2008). The net effect of precipitation thus became insignificant in USB (Chang et al., 2017). The

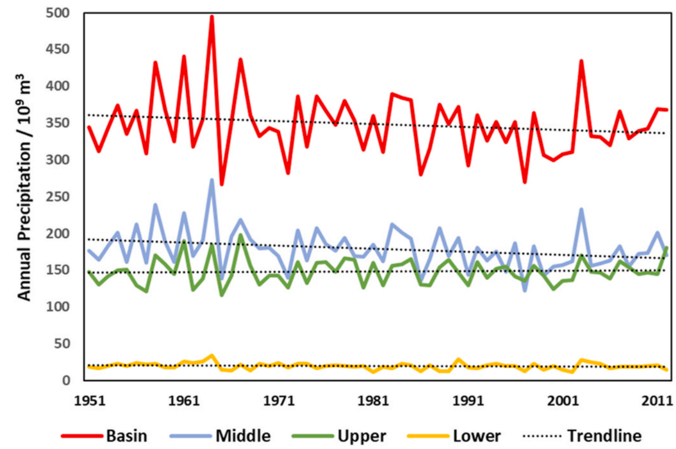

Fig. 4. The annual precipitation in YRB and its sub-basins (Kong et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

decreasing trend in precipitation was chiefly observed in major parts of MSB and LSB (Chang et al., 2017; Liu and Cui, 2011). The river discharge in the Loess Plateau region of MSB also displayed more sensitivity to precipitation than potential evapotranspiration (Liang et al., 2015; Wu et al., 2017a). The reduced precipitation in LSB should not affected the basin run off much, owing to smaller size of the sub-basin and its insignificant contribution to the river flow. The negative impact of declined precipitation was, therefore, limited to MSB only.

3.2.2. Temperature

The temperature in the YRB displayed an average rise of around 1.28 °C/50 yr (Yang et al., 2004). The temperature change was not uniform in the basin and neither its impact. Due to varying geographical and vegetation characteristics, the sub-basins hydrology responded differently to the change in temperature. The following section takes a comprehensive account of such impacts in the sub-basins.

3.2.2.1. Degradation of frozen soil and permafrost in the source region of Yellow River. With increased warming, few studies reported degradation of frozen soil and permafrost layer in the source region (Ma et al., 2019; Niu et al., 2016; Wang et al., 2018a,b). The annual mean air temperature here, around -4.4°C to 7.5°C, is increasing at the rate of 0.39°C/10 yr (Ma et al., 2019). The permafrost area, as well as the maximum frozen depth, both showed a decreasing trend (Wang et al., 2018a). Between 1965 and 2014, the maximum thickness of seasonally frozen soil decreased at the rate of 3.47cm/10 yr. In the past 50 years, around 23 % of the permafrost degraded into seasonally frozen ground (Wang et al., 2018a). Such deterioration of the permafrost region hypothetically enhances the thickness of active layer that allow increased water infiltration. Such condition supposedly increases the base flow in winter, and alter the regional hydrology and the distribution of summer precipitation (Wang et al., 2017b, 2019a).

The same phenomenon, however, was not observed in the case of source region, possibly due to the interference of several lakes and wetlands in the catchment, which conceivably reduced the visibility of such impacts (Wang et al., 2017b). The situation still sends a warning about emergence of such phenomena in future if the deterioration continues. Wang et al. (2018b), on the other hand, concluded that the degradation of frozen ground, from 1965 to 2003, contributed 32.6 % to the total decline in annual streamflow in the source region. Such findings, however, appear insignificant owing to a minor change in annual runoff in the source region (Shi et al., 2017).

3.2.2.2. Change in evapotranspiration. The temporal change in reference evapotranspiration (ET_0) may affect the ratio of river runoff to precipitation. A change in ET_0 can be triggered by diverse factors, including temperature that is widely affected by climate change. Wang et al. (2012b) observed a mixture of both negative and positive trends in change of annual ET_0 in the basin, without reflecting a single specific spatial pattern or trend.

Sub-basin-wise, the study observed a significant increase of annual ET_0 in USB, mainly in the source region, primarily caused by a rise in the mean temperature, which perhaps negatively affected the runoff process there. Meng et al. (2016), affirming the same, reported an increase in evapotranspiration in the source region that contributed 97 % to the observed reduction in runoff there in the 2000s. Its quantitative impact, however, remains minor at the basin level because of a small change in runoff in the source region. Such impact of temperature was offset by change in other climatic variables (such as reduced sunshine duration, decline in wind speed, etc.) in several other parts of the basin, thus also resulting in decreasing trend (Wang et al., 2012b). For example, the MSB showed a mixture of both positive and negative trends. LSB was dominated by a decrease in annual ET_0 owing to the reduced sunshine duration.

The increase in temperature, therefore, mainly showed a tangible effect on the evapotranspiration in certain parts of USB only, which negatively affected the run off process there.

3.3. Anthropogenic activities

YRB has been experiencing growing anthropogenic activities that negatively affected the river, both quantitatively and qualitatively, by reducing its flow and deteriorating its water quality.

3.3.1. Quantitative impacts on flow

Numerous studies, taken at the basin and sub-basin scale, estimated the relative contribution of human activities and climate change on the runoff change. The studies, at the basin level, perceived anthropogenic activities as a firmly dominating pressure responsible for 55% –92 % of the observed reduction in basin runoff (Kong et al., 2016; Miao et al., 2011; Wang et al., 2012a). At the sub-basin levels, the results were similar except for the source region in USB (Wang et al., 2019b). The lower part of USB (e.g. Xiliugou basin) was again dominated by human activities that induced 68 % of the total reduction in runoff there in the 2000s (Yao et al., 2015). Similarly, the studies from MSB, focusing on the Weihe River basin and Loess Plateau, asserted human activities as the most dominating factor that caused 73 %–90 % of the total reduction observed in runoff there in the recent decades (Chang et al., 2015; Wu et al., 2017a). Such studies validated the anthropogenic activities as the emerging and most dominant pressure affecting the runoff in recent decades.

While finding human activities as the most important pressure in the basin, it is further desirable to enlarge insight on such key activities from perspectives of land-use change, water and soil conservation, water comsumption, etc.

3.3.1.1. Land-use change. Several studies in YRB offered data on temporal change in land-use classes (Fig. 5). Li et al. (2017b) and Wang et al. (2010a), both presented a temporal change in land-use classes in YRB for the period 1980–2010 & 1990–2000 (Fig. 5A and 5E). Both results, however, failed to indicate a significant change at the basin level. Other studies, carried at smaller sub-basin levels, also reported insignificant changes (Fig. 5B, 5C, 5D, 5F, and 5G). Such insignificant modification in land-use classes should barely affect or change the basin's capacity to generate runoff. It is still possible to have changes in spatial distribution

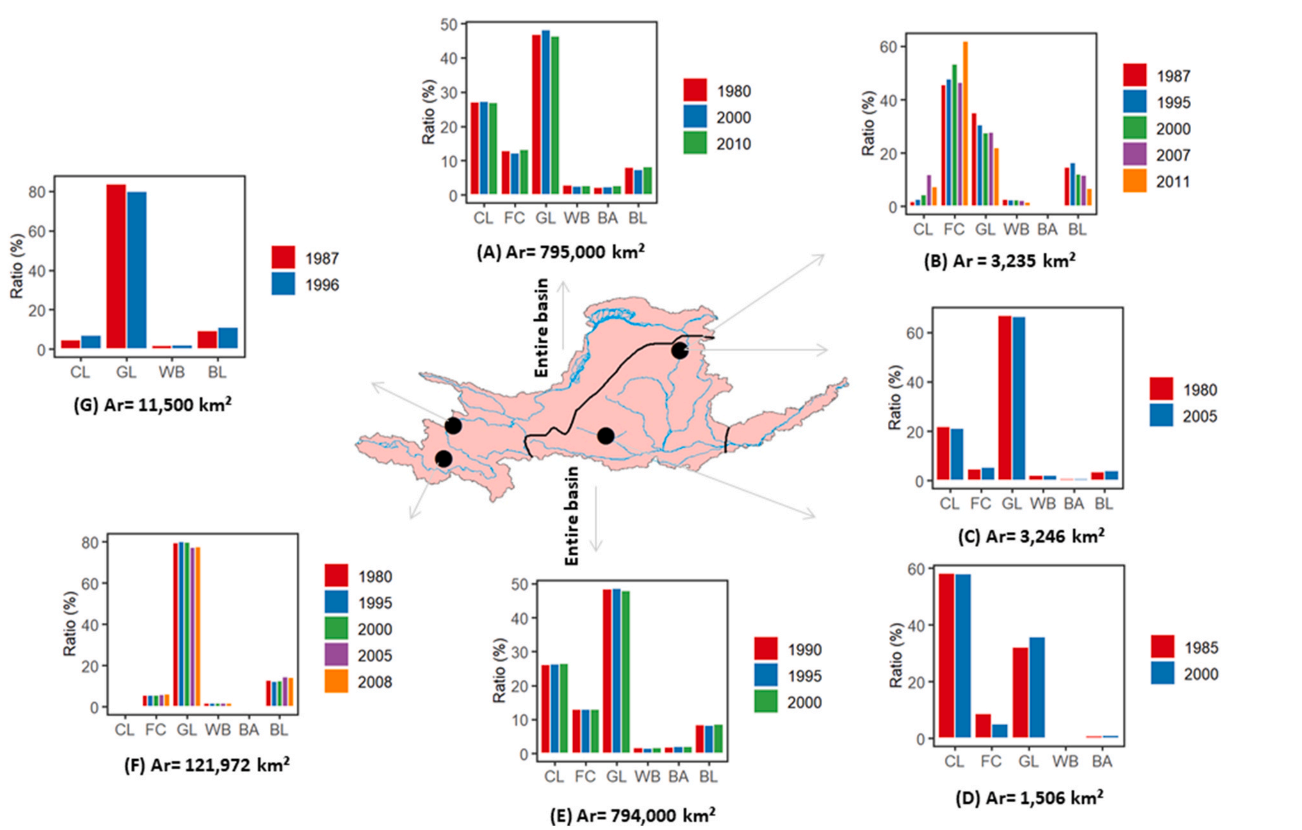

Fig. 5. Temporal change of land-use in YRB (A & E), Huangfuchuan River basin (B &C), Heihe River basin (D), Yellow River Source Area (F), and Gonghe basin (G) (Ar= Area, CL=Crop land, FC=Forest cover, GL = Grass land, WB= Water bodies, BA= Built-up area, BL=Bare land) (Li et al., 2009, 2017b; Pan et al., 2015; Wang et al., 2010a; Xu et al., 2015; Zeng et al., 2003; Zuo et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of these classes without changing their size, which could have affected the basin hydrology to some extend. A major transformation in the spatial distribution of classes, within 20–30 years, seems a less likely event in YRB.

On an important note, Xu et al. (2015) and Zuo et al. (2016) studied the same watershed in MSB but reported a dissimilar result for the land-use classification (Fig. 5B and 5C). It was possibly caused by the use of satellite data having different resolution (100 m and 30 m). The high-resolution data, however, still didn't affirm any major land-use transformation. Thus believing our gathered data, land-use changes indeed appeared insignificant, and therefore it should not significantly reduce or change the basin runoff generation capacity. Such findings were further supported by the other studies, such as Li et al. (2009), that evaluated the land-use change (between 1985 and 2000) in the Heihe catchment (in MSB). The study found that land-use change contributed 9.6 % to the observed reduction in runoff there. There is also no denying that some part of the sub-basins might have undergone significant land-use changes, leading to a significant transformation in its regional hydrological cycle. For example, Yang and Lu (2018) found that the land-use change, caused by the conversion of cropland into forestland and grassland, reduced the runoff by 13.8% in Yanhe River basin in Loess Plateau, MSB. However, the entire basin hydrology should be least affected by such minor land-use changes.

3.3.1.2. Check dams construction and revegetation in the Loess Plateau region (MSB). By 2002, the creation of about 113,500 check dams in the Loess Plateau region had significantly affected the river runoff (Xu et al., 2004). In 2011, the region was left with only 5,470 main check dams (size of >500,000 m^3) and 52,444 small (size of <100,000 m^3) and medium-sized dams, as the remaining check dams were perhaps filled by sediment deposits (Guo et al., 2021; Xu et al., 2018). The check dams were built to control sediment load of the Yellow River. Observing the benefits, a plan was introduced to construct additional 47,000 check dams between 2010 and 2015 (Jin et al., 2012). The studies, however, claimed that the large-scale construction of check dams also retained a significant proportion of the runoff, thus reducing the Yellow River flow. For example, Li et al. (2016) found that check dams, between 1990 and 1999, contributed 24.8 % to the total decrease in annual runoff in Huangfuchuan River basin (in the Loess Plateau, MSB). That contribution later reached as high as 65.2 % between 2000 and 2012. Similarly, in the Wuding River basin in MSB, Shi et al. (2019) found that check dams reduced the runoff by 12 %. As per a projection by the Ministry of Water Resources of P.R. China, the check dams perhaps already reduced 4.3–5.5 BCM of water yield in YRB (Jin et al., 2012). Such effect of check dams apparently seems significant in MSB, however, the exact quantitative effect still needs to be measured.

Certain parts of the Loess Plateau region in MSB have undergone significant revegetation under the “Grain for Green” program, partially using non-native plants (Chen et al., 2015b; Deng et al., 2016). Between the years 2000 and 2010, a large-scale new vegetation area, comprising forest, shrub, grassland, and reduced farmland, increased the regional evapotranspiration at the rate of 4.3 ± 1.7 mm/yr^2. It reduced the ratio of river runoff to precipitation, leading to an additional reduction in the river runoff by 0.5 ± 0.3 mm/yr (Feng et al., 2016). Feng et al. (2016) additionally concluded that an increase in evapotranspiration also triggered a loss in soil water content by 2.4 ± 0.9 mm/yr. Several studies confirmed such decline in soil water content in recent times, which also induced formation of a dried soil layer (An et al., 2017; Chen et al., 2015b; Jia and Shao, 2014; Wang et al., 2010b). Soil water is considered one of the important limiting factors for vegetation growth and ecosystems sustainability, particularly in arid and semi-arid regions (An et al., 2017; Deng et al., 2016). In the Loess Plateau, an aggravated soil desiccation thus became a threat to the growth and stability of regional vegetation (Chen et al., 2008; Jia and Shao, 2014; Li et al., 2008). Such unsuitable vegetation may impair or reverse the soil conservation efforts and may trigger increased sediment load into the Yellow River. In the future, therefore, a sustainable water and soil conservation strategy should be implemented.

3.3.1.3. Agricultural, industrial and domestic consumption of water. A rise in population, accompanied by a rapid economic and agricultural development in YRB, triggered water-intensive activities that increased the water demand in the basin. The annual water consumption in the basin increased from 12 BCM in the 1950s to 30 BCM in the 1990s (Fig. 6). The water consumption in 2012 was already higher than 40 BCM (Kong et al., 2016). The agriculture sector was a major consumer of water. It was found accountable for 85 –92 % of the total water consumption in the basin. In terms of water consumption in YRB, the agriculture sector was followed by industries (5 %–10 %) and domestic sector (3 %–5 %) (Fig. 6D and 6E) (Liu and Xia, 2004; Ringler et al., 2010). The agricultural consumption of water increased over the time owing to expansion in irrigated areas in the basin (>350 %), from 14, 000 km^2 (in the 1950s) to 48,000 km^2 (in the 1990s) (Liu and Xia, 2004; Liu and Zhang, 2002; Ringler et al., 2010). It led to an increase in water use by more than 250 %.

Sub-basin-wise, water consumption always remained the highest in USB, which was attributable to its large irrigated area (Fig. 6). USB was followed by LSB and MSB in terms of water consumption in the basin (Liu and Zhang, 2002; Ringler et al., 2010; Wang et al., 2019b). MSB experienced a threefold increase in irrigated area (between the 1950s and 1990s) that made it nearly the same size as the irrigated area in USB in the 1990s (~13,300 km^2). Interestingly, the region in and around LSB witnessed the highest expansion in the irrigated area (nearly seven times) due to the land fertility and land suitability for agriculture. It included areas beyond the basin boundary, such as the part of Henan and the entire Shandong province, that relied on the Yellow River water for irrigation (Leong, 2013). The irrigated area around the lower reach in the 1990s reached a massive size of ~22,230 km^2. It dramatically enhanced the water consumption from the lower reach by six times, with 92 % of the water used in agriculture. Using the 1990s data from Liu and Zhang (2002) and Ringler et al. (2010), the irrigation water consumption per unit area in USB, MSB, and LSB was estimated to be about 0.94 million cubic meters per km^2 (MCM/km^2), 0.36 MCM/km^2, and 0.51 MCM/km^2, respectively. The river water was additionally abstracted for residential and industrial consumption in the cities such as Jinan, Qingdao, and Tianjin (Giordano et al., 2004). The region around the lower reach also had a high population density of 750 person/km^2 which consumed 525 m^3/capita of water (relatively higher than the available water resources) (Feng et al., 2012; Leong, 2013). The region thus relied heavily on the river. The lower reach, therefore, witnessed rapid water diversions and intense withdrawals (Liu and Xia, 2004). Most importantly, LSB contributed very little to the Yellow River flow but withdrew heavily.

3.3.2. Qualitative impact caused by pollution

3.3.2.1. Waste water discharge. The Yellow River flows through major mining sites, industrial regions, and large cities that discharge pollution to it. In past, about 50 % of the river was reported to be heavily polluted and referred to as biologically dead (Fig. 7) (Futehally et al., 2010). In 2008, the Yellow River was receiving nearly 4 billion tons of wastewater, equivalent to 8 % of its annual mean runoff (Branigan, 2008; Moore, 2008). Around 70 % of such waste discharge was coming from industry and manufacturing, and 23 % from households (Branigan, 2008; Daily Mail, 2008). In addition to point sources, the agriculture runoff carrying fertilizer and pesticides contributed nutrients and heavy metals, etc. The contribution of point sources, particularly for nitrogen pollution, was much higher compared to non-point sources (Xia et al., 2002b). The anthropogenic flux of such nutrients became apparent in the lower section of the upper reach and middle reach, caused by both

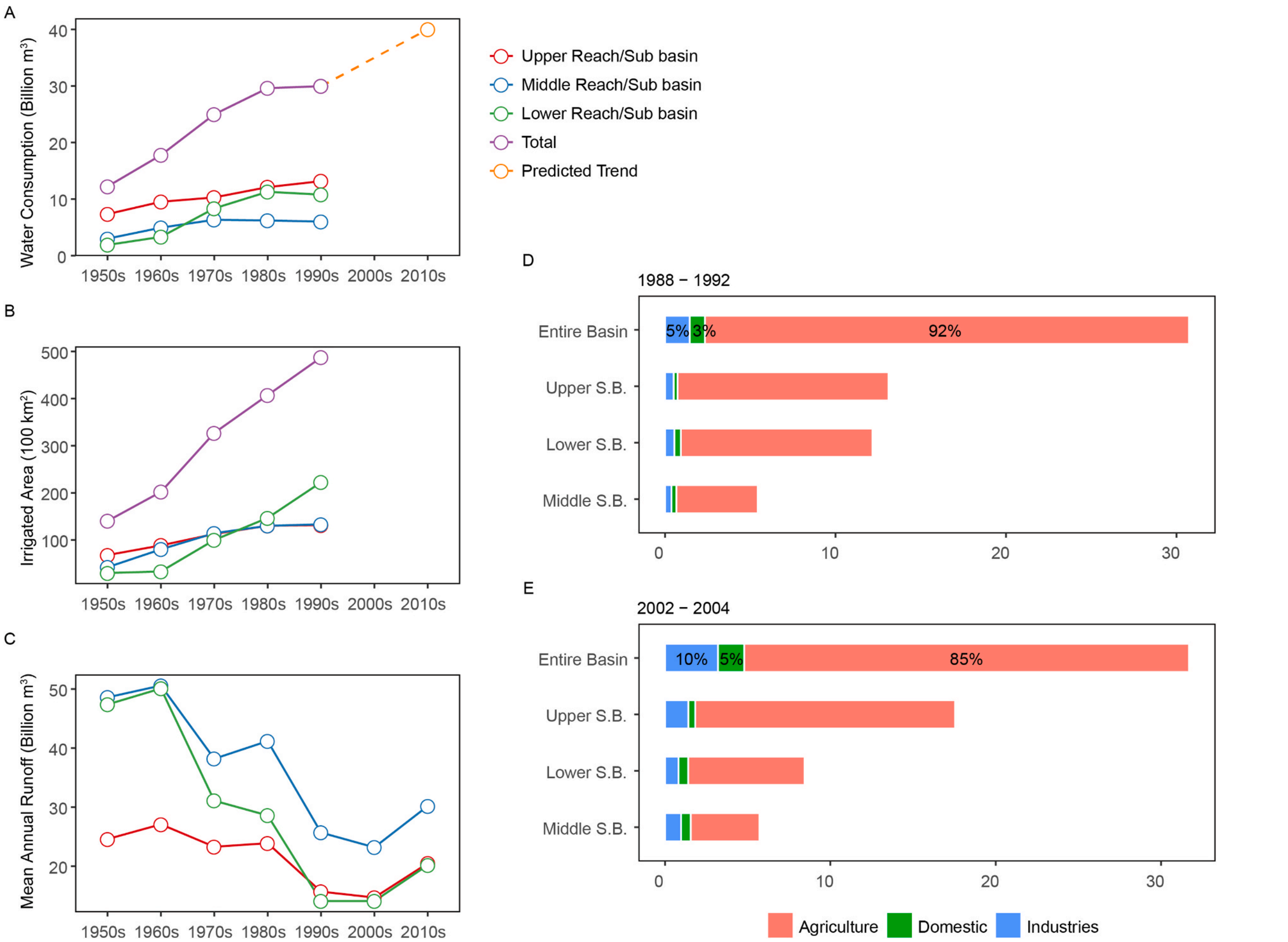

Fig. 6. Temporal change in (A) quantity of water consumed in YRB (Kong et al., 2016; Liu and Zhang, 2002), (B) irrigated area in the sub-basins, (C) mean annual runoff in the reaches (Shi et al., 2017). (D) and (E) depicts the utilization of YRB water by different sectors in the period 1988–1992 & 2002–2004 (Ringler et al., 2010; Chen, 2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

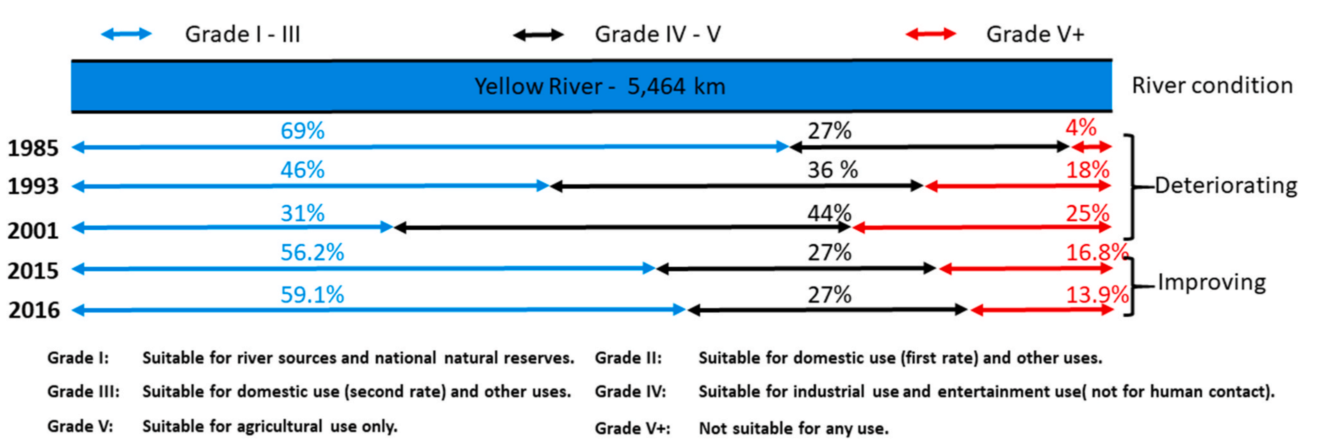

Fig. 7. Temporal change in the water quality of Yellow River (China Water Risk, 2017; Giordano et al., 2004; Wang et al., 2016). The criteria to classify river water into different grades can be seen in Table A.2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

intensive agriculture and urban activities (Yue et al., 2017).

The rich natural resources of MSB allowed substantial industrial growth in the region (Feng et al., 2012). Thereby, many of the tributaries carrying polluted water of class IV and worse entered the Yellow River in downstream of the middle reach, thus making MSB the largest source of pollution (Han et al., 2016; Zhao et al., 2020). For example, the Weihe River and Fenhe River in MSB had a high proportion of waste water to their flow (~10.4 and 21.3 %, respectively) (Chen et al., 2004). The lower reach, on the other hand, had only a few tributaries; thus relatively less pollutants were added in this stretch (Yue et al., 2017). Poor water quality was observed in both the middle and lower reaches. In dry years, the river usually had a higher concentration of pollutants due to less dilution (Chen et al., 2004).

3.3.2.2. Excessive nitrogen. Few studies comprehensively focused on the nitrogen pollution in the river (Tao et al., 2010; Xia et al., 2002b). In 1998, the average total nitrogen in the mainstream river was 3.7 mg/L, and it ranged between 1.19 and 5.46 mg/L (Chen et al., 2004). The total nitrogen concentration showed an increasing trend from the upstream to downstream. In contrary to the mainstream, the total nitrogen concentration in tributaries were relatively higher with an average of 10.5 mg/L, which further increased to a maximum of 53.8 mg/L (in 2018) in heavily polluted tributaries, such as Fenhe River (Chen et al., 2004; Yang et al., 2018). Nitrogen in the mainstream river dominated in the form of ammonium nitrogen ($NH_4^+ - N$) and Nitrate nitrogen ($NO_3^- - N$), and both found in the range of 0.06–0.58 mg/L and 0.53–1.89 mg/L, respectively (Xia et al., 2002b). Xia et al. (2002b) concluded point sources as the dominating source of nitrogen pollution in the Yellow River and its tributaries. Later, based on a statistical correlation between nitrogen load and other factors, Tao et al. (2010) suggested the increase in nitrogen loading was largely influenced by population growth (sewage disposal) and application of nitrogenous fertilizer, rather than the industrial discharges.

3.3.2.3. Other pollutants. Concerning other pollutants, certain parts of the Weihe River showed significantly higher concentrations of polycyclic aromatic hydrocarbons (with a mean value of 835 ng/L and range of 351–4427 ng/L in water dissolved phase), which was possibly contributed by pyrolytic (coal thermal power plants) and petrogenic sources (petroleum industry and chemical plants) (Chen et al., 2015a). Similarly, in the Fenhe River, a higher concentration of sulfate was contributed by coal mining (Yang et al., 2018). Zhao et al. (2020), using water quality index (based on physico-chemical properties, such as biological oxygen demand (BOD), chemical oxygen demand (COD), Nitrate nitrogen, Coliform, etc.) confirmed pollution and upstream-to-downstream degradation in water quality of nine important tributaries in MSB and LSB, with the Jindi and Dawen Rivers (in LSB) being most polluted. The Yellow River pollution, particularly, the toxic effluent from chemical and petrochemical enterprises made multiple sites highly hazardous and had a detrimental effect on several species, ecology, and human health (China Daily, 2014; Reuters, 2007). The use of such polluted water in irrigation also exposed farmers to health risks, and such water simultaneously contaminated the crops (Ivanova, 2013).

Such findings were the indicators of a serious Yellow River pollution, which seems to be largely contributed by MSB, followed by LSB. A systematic and comprehensive spatial data depicting water quality in the river was still difficult to find in literature. Recently, the river water quality improved by 5.2 % in 2018 compared to 2015 (Dong, 2020). Probably the revision of environmental protection law in 2014, and further placing a water pollution and prevention action plan in 2015, known as the "10-point water plan", contributed to such progress (Fig. 7) (Han et al., 2016; Xu and Chen, 2019). Such measures strengthened environmental law enforcement, reduced pollutant discharge, and offered market mechanisms to control pollution. With such an ambitious plan and strict monitoring, if translated into effective action, the Yellow River water quality is further expected to improve.

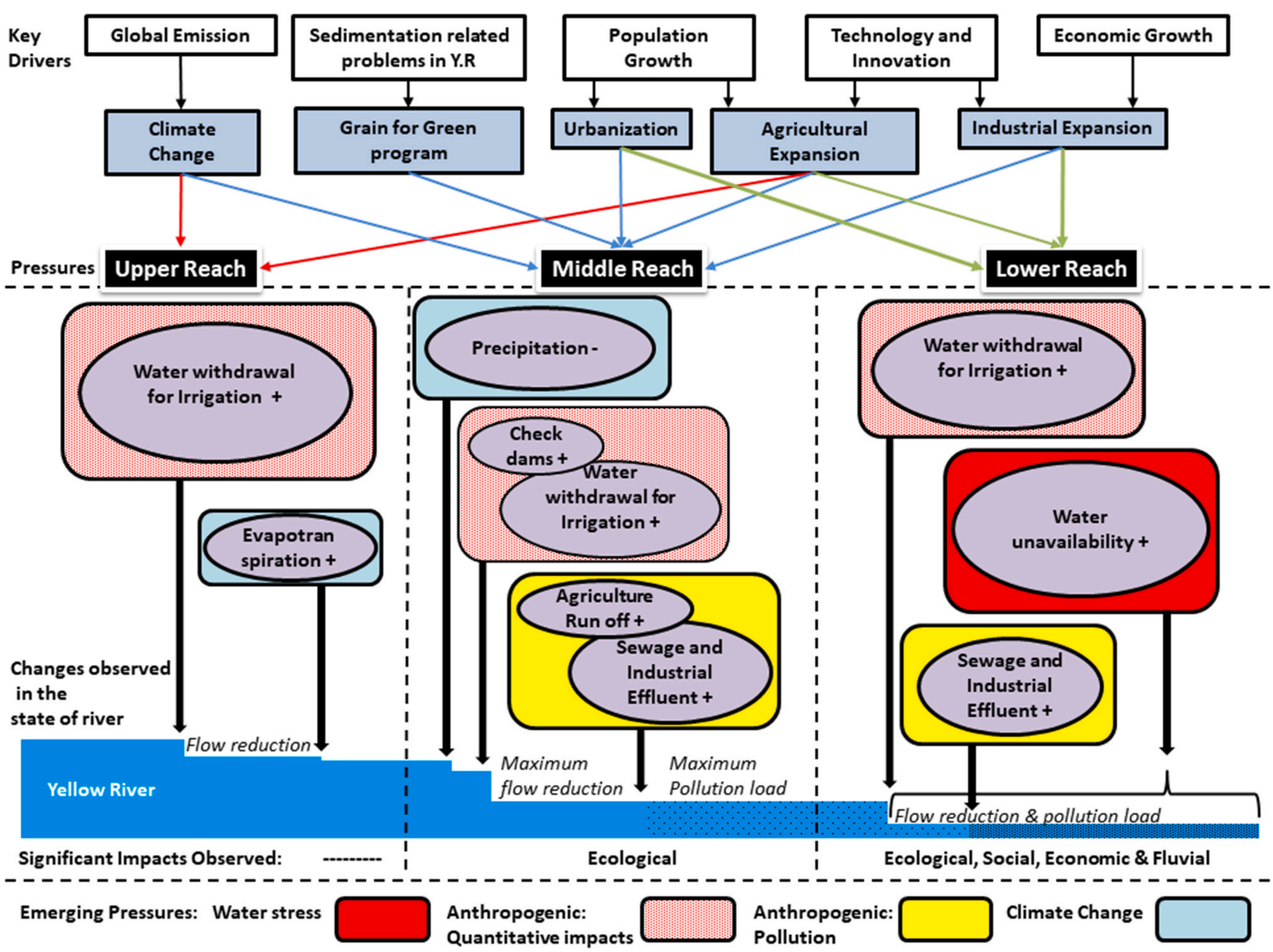

Fig. 8. The key drivers, pressures, and impacts acting in YRB. The size of rectangular boxes signifies the relative severity of the impact caused by corresponding emerging pressures (depicting major and minor emerging pressures, for representation purpose only). The "+" and "–" sign indicates a recent increase or decrease in the factor. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Critical emerging pressures, their drivers, and impacts in the basin

The major emerging pressure, having social, economic, and ecological consequences, was water stress, which was triggered by an exponential rise in anthropogenic activities in the basin. The serious water stress, largely observed in the lower reach, was caused by an increased consumption of water, as well as a rise in pollution that rendered much of the available water useless (Fig. 8).

Quantitatively, the mean annual runoff in lower reach reduced from 47 BCM in the 1950s to 14-20 BCM in the period 2000s–2010s. Besides a rise in industrial and domestic consumption, the root cause of such reduction lay in the intensive increase in agricultural consumption of water, specifically for irrigation (28 and 27 BCM in the period 1988-1992 and 2002-2004, respectively). The temporal change in land-use classes had shown no significant changes in the basin, but a significant conversion of rainfed agriculture into irrigated regions perhaps led to increased water consumption in the last few decades. USB alone abstracted the maximum water for agriculture (12 BCM in the 1990s), followed by LSB (11 BCM in the 1990s) and MSB (5 BCM in the 1990s). The irrigation water use per unit area, indicating the irrigation efficiency, varied from USB to LSB, with USB showing relatively poor efficiency (0.94 MCM/km^2) compared to MSB and LSB (0.36–0.51 MCM/km^2).

The Murray Darling Basin (MDB) in Australia, having similar characteristics as YRB (such as drying river condition, intensive extraction of water for agriculture, and comprising semi-arid/arid regions), adopted several water-efficient technologies and practices in the recent past to enhance its irrigation efficiency and to save water (Koech and Langat, 2018). The average irrigation water use per unit area there, from 2014 to 2017, was 0.43 MCM/km^2 (Koech and Langat, 2018). In comparison to MDB, USB indeed demonstrated poor irrigation efficiency, probably owing to the easy availability of water that triggered its wastage and inefficient water use practices. In addition, the creation of numerous check dams in MSB also retained a significant amount of water (~5 BCM by 2020). The check dams thus became conflicting solutions for checking erosion. However, such a case was also reported from India where check dams produced undesirable side effects (Singh and Singh, 2019).

The role of pollution in amplifying the water stress was undisputable when it made 13.9 % of the river water unsuitable for any use in 2016 (Fig. 7). Such a situation was even more distressing before 2016. Pollution in the Yellow River was caused by agricultural runoff, sewage, and industrial effluent; largely from MSB, followed by LSB. Some nutrient pollution was also added by the large agricultural region of USB. A high pollution level was observed in the tributaries of MSB. Pollution in the mainstream river took a serious turn mainly in LSB, where the pollution level perhaps also exaggerated owing to the abated flow there. The use of such polluted water for irrigation impose health risks to farmers as well as the consumers of their agricultural products. Such pollution additionally impacted the environment and ecology.

The impact of climate change currently contributing least to the problems in YRB (reducing only ~2.3 BCM of annual runoff in the 2000s), and its negative impact largely observed in MSB only (Kong et al., 2016). In the future, a continuous degradation of permafrost soil may seriously affect the regional hydrological cycle of the source region (USB). While digging into the future impacts of climate change in YRB, Liu et al. (2011) surprisingly suggested the river streamflow (under different scenarios) may increase by 11.5–42.9 % relative to the average streamflow between the years 1961 and 1990. Such a favorable outcome of climate change should alleviate water stress to a certain degree but should also trigger floods. In contrast, other studies rather suggested that climate change may aggravate both water shortage and flood events in the basin (Wang et al., 2015; Zhu et al., 2016). Wang et al. (2015) evaluated that the basin runoff in coming decades may decrease by 0.53–9.67% relative to the period 1991–2010, with a high spatial and decadal variability. Such contrasting conclusions, while ensuring an enlarged role of climate change in the future, hint us to expand our understanding of climate change based on the global evidence, updated information, and comprehensive research.

Overall, MSB seems to have the highest negative effect on the river, both in terms of reducing flow and adding pollutants. In addition, the revegetation activity in the Loess Plateau also reduced the river runoff.

3.5. Pathways to address the key emerging pressures

With serious consequences, the water stress in the basin, largely fueled by the agricultural sector, became the foremost priority to manage. Such high agricultural consumption of water has already sparked water stress in a few major rivers around the globe, such as the Indus River in Pakistan, Murray-Darling River in Australia, Colorado River in U.S., etc. (Davies et al., 2018; Heggie, 2020; Howard and Borunda, 2019; Irfan et al., 2019). The overdrawn water for agriculture and irrigation use is only expected to increase due to global warming and increasing population and food demand (Haddeland et al., 2014; Leng et al., 2017; Rodríguez Díaz et al., 2007).

To address such growing water insecurity in Northern China (including YRB), the government called for a capital intensive-heavy engineering approach, known as 'South-North Water Transfer Project' (SNWTP), with an initial investment of ~RMB 10,769 billion between 2004 and 2013 (Rogers et al., 2019; Webber et al., 2017). It is the largest interbasin water transfer scheme that became partially operational in 2013. After the entire completion of its two key routes (Eastern and Middle), the project would be able to deliver 27.8 BCM of water annually to the northern water-stressed region (including the part of YRB) from the Yangtze River and its tributaries in the south (Webber et al., 2017). Implementing SNWTP, however, only intensified challenges for YRB by enlarging its water management to greater than a basin-scale (Webber et al., 2017). Besides adding several institutional and governance challenges, the transported water itself became relatively expensive than the locally available water, due to the high cost involved in the construction, controlling the pollution, resettling affected people, pumping water, operational and maintenance cost, etc. (Rogers et al., 2016; Sheng et al., 2020; Webber et al., 2017).

In contrast to the engineering solutions, another approach widely debated was managing water demand by saving water, increasing water use efficiency, and improving management. Previous studies highlighted such conservation and regulation of water, specifically for the irrigation water, can be achieved by appropriately implementing economic and market-based instruments, such as water pricing, taxes, subsidies, water trading (water right transfer); and controlling pollution as well as adopting water-saving technologies (Pietz and Giordano, 2009; Ringler et al., 2010; Wohlfart et al., 2016). Introducing such reforms in the agricultural sector of China, however, suffered limitations. An increase in the price of (currently underpriced) irrigation water can affect the revenue and welfare of farmers who were already least benefitted from the economic development. High pricing may additionally encourage the exploitation of cheaper groundwater resources, which may add salinity to the soil. Thus finding an appropriate water price for farmers remains a major hurdle. In water trading, the agricultural water can be allocated to the industries having higher economic efficiency of water use, and in return, industries are supposed to compensate the agriculture sector by offering water-saving technologies and welfare to the farmers. Under such provision, inter-provincial water trading also becomes a possibility that can reduce water wastage in USB and allow its efficient use in MSB and LSB. Such implementation, however, also requires a true water right and an effective market system for the water.

The use of technology to save water and to enhance water use efficiency in farms using subsidies and grants seems a promising option. A study of such implementation in MDB, however, suggested otherwise, which found farmers only extended their irrigation area using the saved water (Koech and Langat, 2018). The net saving of water at the basin level thus became insignificant due to the rebound effect. With such potential ideas and examples of failures, successful management of water demand seems to require serious adaptation in the agriculture sector that also demands additional investment and adaptive institutional changes (Cosgrove and Loucks, 2015). As pollution is also a contributor of the water stress, controlling pollution is equally important. Though it is easier to control the point source of pollution, managing non-point sources remains the biggest hurdle. Controlling such sources of pollution requires effective monitoring and implementation of improved policy instruments, coupled with the use of innovative technological solutions (such as the Teabag method, use of P-Adsorption agents, etc.) (Zamparas et al., 2019, 2020). With a surge in new pollutants in water, the standards to classify water quality should also be updated (Han et al., 2016).

4. Conclusion

The review offered a knowledge basis for improved management of the Yellow River by highlighting a holistic view on the emerging pressures distressing the river and its functions. The analysis identified critical 'water stress' in the lower reach as the most important concern, which was largely caused by a reduced flow/runoff in the lower reach, from 47 BCM (annually) in the past to 14-20 BCM in recent decades. Such reduction was largely contributed by increased anthropogenic activities in the basin, specifically from the increased agricultural withdraw ($\geq$27 BCM) and the check dam's retention of water ($\sim$5 BCM), with a smaller contribution from climate change as well ($\sim$2.3 BCM). The increased pollution in the river, besides adding ecological and health challenges, also contributed to water stress by making certain parts of the river (13.9 % of the river in 2016) unsuitable for any use.

Historically, the adoption of large-scale hard (engineering) solutions in YRB often made irreversible changes, that mostly evolved and transformed the problems, and reproduced more complications. Currently, moving away from such large-scale hard solutions or integrating them with adaptive soft solutions (such as demand management in the case of water stress) as per the dominant socio-cultural settings should be of large public interest. Given the basin size and its current complexity, none of the interventions discussed (in section 3.5) may assure success alone, however, considering such reforms could be a key step toward approaching cost-effective and sustainable solutions for the future. It is evident that understanding and resolving issues in an isolated manner may invite further complexity or failure in long term due to the presence of other unaddressed pressures. The current management approach thus also needs to make a shift from focusing on a single issue (that affecting the river today) to multiple concerns that recognize future water challenges under the impact of climate change, rapid urbanization, ongoing other projects, pollution load, floods etc.

Certain decisions are already made on the key problem of water stress in YRB, thus the way forward is to avoid failures through learning and adapting to upcoming challenges. Grafton (2019), observing similar problems in MDB, correctly highlighted a need for independent reviewing and auditing processes that allow timely reforms on key decisions and actions based on updated information and evidence produced by diverse disciplines. For example, eradicating undesirable negative effects of the "Grain for Green" program and taking a decision based on an improved understanding of climate change would lay a strong foundation for timely progress. Additionally, a genuine participatory approach, involving all relevant stakeholder, offer a pathway to an acceptable and sustainable management plan that balance environmental needs to the socio-economic interests. Further, a decision based on a localized account of the problems, as illustrated by the example of land-use change in some part of the Loess Plateau, may not effectively address the key problems at the basin level, thus always requires building an insight at the basin level.

Declaration of competing interest

None of the authors or any other person have conflict of interest related to the submitted research manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113423.

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