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Review

The Ecological Effect of Ship Canals on Wetlands

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Abstract: Ship canals, which play a crucial role in facilitating transport, exert significant and long-term impacts on wetland ecosystems. For social and economic development, numerous countries have put forward plans for ship canals. This paper reviews the literature on the ecological effect of ship canals on wetland ecosystems, identifies research gaps, and suggests future research directions. Ship canals typically involve high construction intensity, usually including river regulation, ship locks, and water diversion for navigation. The ecological effects of ship canals on wetlands refer to changing wetland hydrological processes, degrading water quality, eliminating wetland botany, disturbing wetland animals, and increasing ecological threats. The cumulative impact can either alter the trend of ecological succession or degrade biodiversity. Thus, there is a need for further research to elucidate the mechanisms by which canals affect wetland ecosystems, enhance the practices for wetland protection associated with canals, and develop a robust evaluation system for green canal projects.

Keywords: ecological effect; environmental impact; ship canals; wetland ecosystems

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1. Introduction

Ship canal refers to an artificial waterway formed by the excavation of land in order to provide waterways for transportation [1]. It is considered a key factor in facilitating economic growth [2]. In the late 20th century, there were about 63,000 km of canals worldwide [3]. With a length of 3500 km, the Grand Canal in China is the longest ship canal in the world [4], whose records date back to the Spring and Autumn periods [5]. The Suez Canal and the Panama Canal are two of the busiest transporting waterways in the world [2,6]. The Suez Canal handles about 12% of global cargo transportation and 30% of container trade annually [7]. The Panama Canal, which was built in 1914, facilitates roughly 5% of global trade yearly, with approximately 14,000 vessels crossing from different countries [8].

The earliest recorded artificial waterway dated back to approximately 4000 BCE, when the Mesopotamians began utilizing waterways for navigation, irrigation, and other purposes [9,10]. Since then, many countries began to build canals, some primarily for navigation. The ten longest canals in the world are listed in Figure 1. The main elements of canal projects include river bending and straightening, dredging, water diversion for navigation, ship locks, revetment works, etc. [11,12], as shown in Figure 2.

Due to the important function in enhancing comprehensive transportation networks and regional economic development, many countries have suggested developing artificial canals, such as the Sethu Samudram Canal [13], the Paraguay–Parana Canal [14], the Istanbul Canal [15], the Nicaragua Canal [16], and the Kra Canal (also known as the Carat Canal) [17]. In 2020, China's Ministry of Transport issued the Outline for the Development

of Inland Navigation, proposing the construction of the Pinglu Canal, the Jianghuai Mainline, the Zhe-Gan-Yue Waterway and the Han-Xiang-Gui Canal. In 2023, the transportation department of Jilin Province in China issued the Outline of Provincial Comprehensive Transportation Network Planning, which proposed the construction of the Songliao Canal. The Pinglu Canal is under construction and scheduled to be finished in 2026 [18], while the other canals issued by the Chinese government are still in the planning stages.

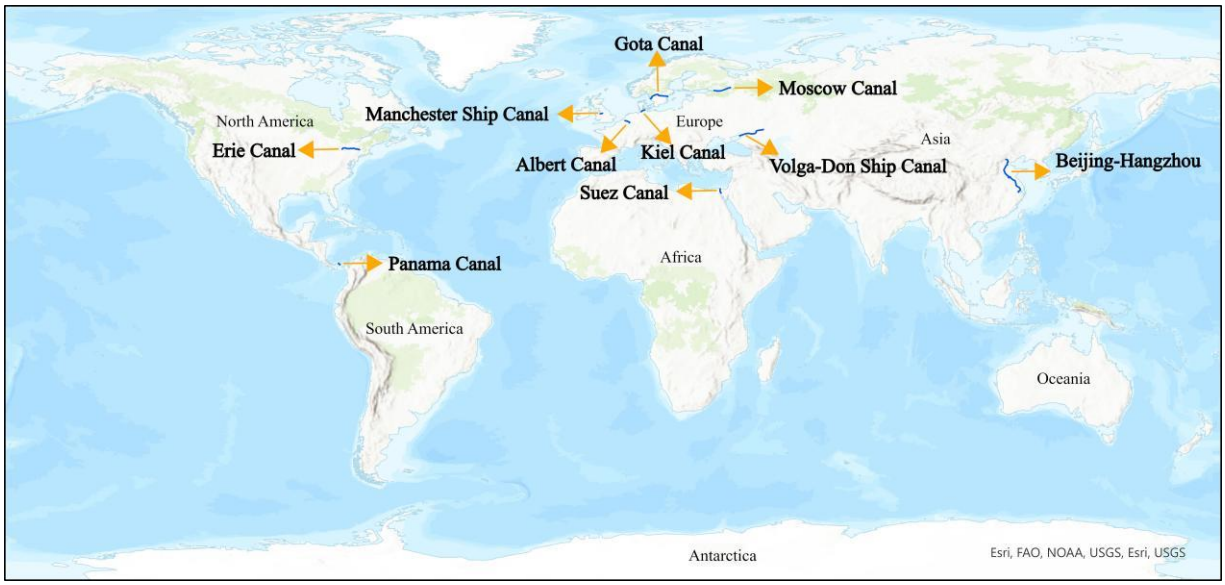


Figure 1. Schematic diagram showing the ten longest canals in the world.

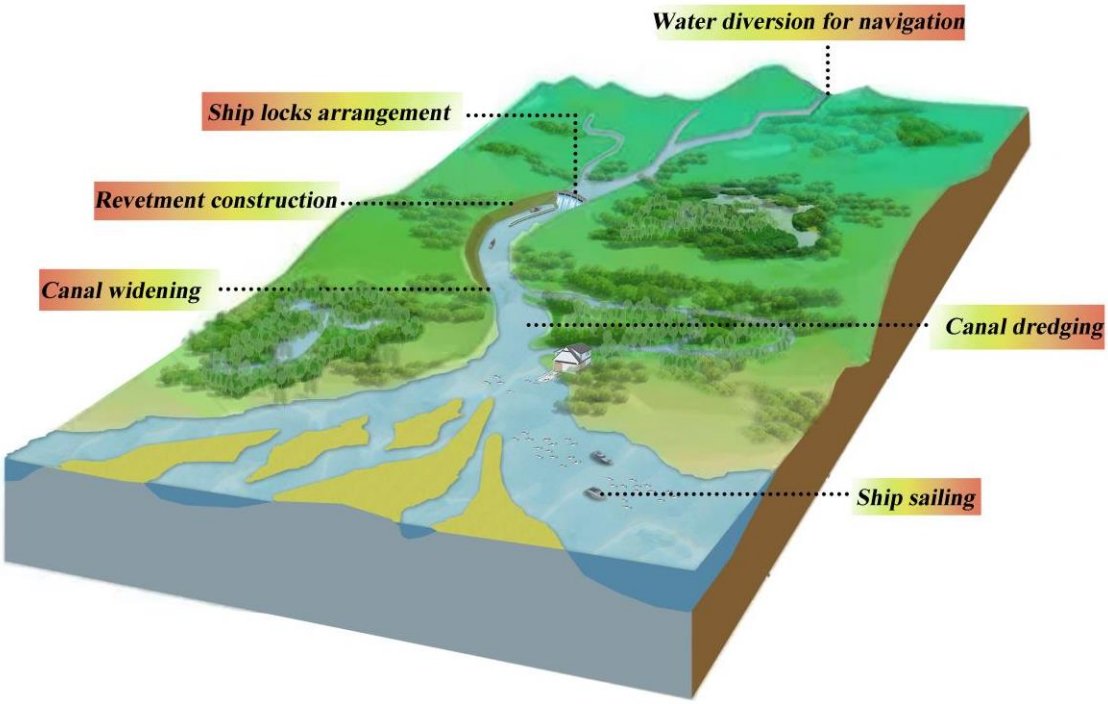


Figure 2. Main elements of canal engineering.

Canals for navigational access can be divided into inland canals and coastal (estuary) canals. This paper provides some basic information (such as country, length, channel classes, and connecting rivers/seas) about canals, including those that have been completed, those in the planning stages, and those under construction, as shown in Table 1. The channel

classes of inland canals are generally less than 5000 tons, such as the Beijing–Hangzhou Grand Canal, the Erie Canal, the Moscow Canal, etc. Coastal canals often serve large ocean vessels, whose channel classes are usually at least 10,000 tons, such as the Suez Canal, the Panama Canal, the Kiel Canal, etc. Canals also establish connections between water bodies to reduce travel expenses and distances [19]. Thus, the novel canal connections provide new ecological corridors when natural waterways are parted [9]. In addition, industries and real estate would increasingly gather along the canal which might receive wastewater and untreated urban stormwater from surrounding areas.

Table 1. Basic information on some famous canals.

Name	Length (km)	Channel Classes/Water Depth	Connecting Rivers/Oceans	Nationality	Status	Author [Ref.]
The Beijing–Hangzhou Grand Canal	1794	Part of the canal for ships of 1000 tons	Qiantang River, Yangtze River, Huai River, Yellow River, and Hai River	China	completed	Jing [20]
The Erie Canal	563	50–60 tons	Hudson River, Lake Erie	USA		Bujaki [21]
The Suez Canal	192.5	The ship's draft reaches 20.12 m	The Mediterranean Sea, Red Sea	Egypt		Lin [22]
The Moscow Canal	128	10,000 tons	Moscow River, Volga River	Russia		Yang [23]
The Kiel Canal	99.8	Water depth 11.0 m	North Sea, Baltic Sea	Germany		Feng [24]
The Panama Canal	81.3	Allows 14,000 TEU vessels to sail	Pacific, Atlantic	The Republic of Panama		Liu [25], MoC [26]
The Plinglu Canal	143	5000 ton	Rongjiang River, Qinjiang River	China	under construction	Han et al. [11]
The Xianggui Canal	About 1200	Above 1000 ton	The Yangtze River, Xijiang River	China	planning	Lv and Jiang [27]
The Gan Yu Canal	About 1300		The Yangtze River, the Pearl River	China		Gao and Jiao [28]
The Sethu Samudram Canal	About 260	12 m	The Arabian Sea, the Bay of Bengal	India		Rao et al. [13]
The Istanbul Canal	About 45	25 m	Black Sea, Marmara Sea	Türkiye		Ceylan Baba [15]
The Nicaragua Canal	About 276	28 m	Pacific, Caribbean Sea	Nicaragua		Chen et al. [16]
The Kra Canal	About 102	25 m	Gulf of Thailand, Myanmar Sea	Thailand		Cathcart [29]

Ship canals, as crucial components of transportation infrastructure, involve intricate construction processes and substantial workloads [11]. Consequently, canals pose a serious threat to river and estuary wetland ecosystems globally, affecting freshwater biodiversity

and the conservation of aquatic ecosystems [15,30]. One of the primary concerns for stakeholders and policymakers in making strategic decisions is the impact of canals on the wetland ecosystem [16]. Canal dredging for navigation could result in loss of wetland scale [31], which would alter navigable water quality and threaten the habitat of freshwater and marine wildlife [32,33]. Cascade ship locks in canals would impede the migration of fishes and other animals [34]. By connecting different basins, ship canals facilitate ecological corridors for non-native species and exotic pathogens [35,36]. In addition, ship-induced waves and noise could profoundly affect beach macrophytes and mammals in the waterway [37,38].

Depending on the features of the canals and their surrounding environments, the impact of canals on ecosystems varies significantly [39]. Numerous studies have been conducted to assess the environmental impacts of canals and explore strategies to mitigate their adverse effects. However, existing research often focuses on specific case studies, such as the effects of ship locks or boat waves, without providing a comprehensive analysis of the overall operation of canals. This review aims to synthesize the ecological effects of canals on various wetland compartments and examine how these impacts cascade into other compartments. The objectives of this article are as follows: (1) what are the economic benefits of these canals; (2) increasing awareness in the ecological effect of canals on wetland ecosystems, especially the ecological losses caused by canals; (3) proposing the existing research gap; (4) proposing future work to mitigate the ecological impact on canal wetlands.

2. Terminologies Used

There are many terms used to describe wetland ecology, including wetland extent and distribution, species diversity, and ecological processes which relate to hydrology or water regime [40]. Drawing on the classification used in several studies [41], this article categorizes the ecological effects of ship canals on wetlands into the following four categories (Figure 3): hydrological process, pollutant process, botany, and animal. The effect on the hydrological process encompasses the impact of hydrological connectivity and the impact of hydrological elements. The effects on the pollutant process include nutrient variation, salt intrusion, and sediment pollutants, such as heavy metals. The effect on botany includes dislocation, biomass loss, and decreased biodiversity. The effect on animals includes biomass reduction, habitat loss, and non-native species invasion.

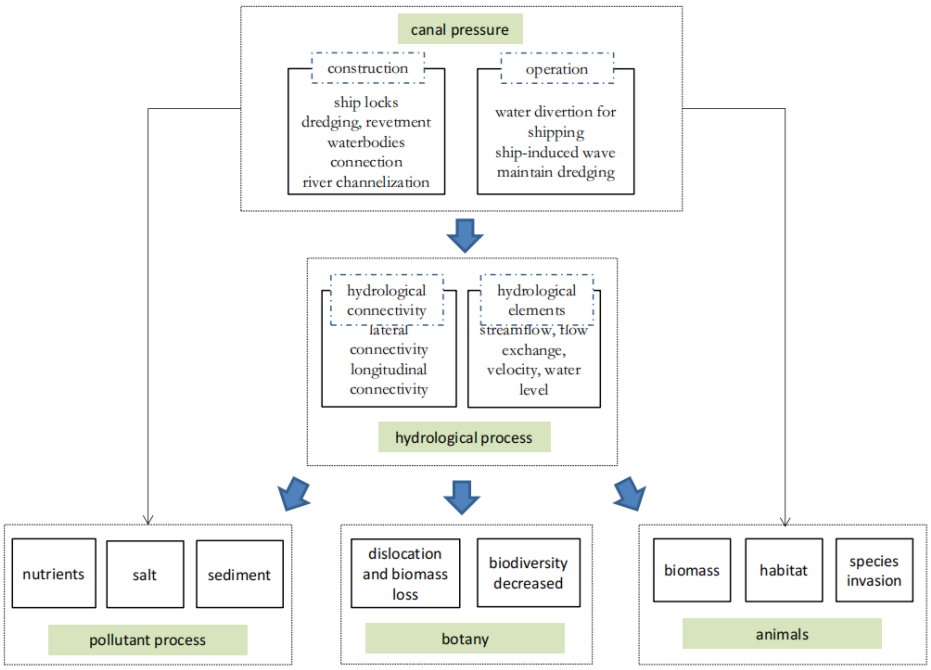


Figure 3. Conceptual overview of ecological effects of canals on wetlands.

3. Economic Benefits

Ship canals have made great contributions to the development of the economy. First of all, canals can provide convenient shipping routes and shorten transportation costs. From the east coast of North America to Asia, the Panama Canal has reduced voyage distances by more than 8500 miles [42]. Transporting Liugang iron ore through the Pinglu Canal to the Beibu Gulf Port route is expected to save 3–16 yuan/t compared to the existing Beibu Gulf Port route [43]. Between the North Sea and the Baltic Sea, the Kiel Canal traverses northern Germany, saving ships an average of 250 nautical miles and correspondingly lowering fuel usage [44]. By offering a more efficient and cost-effective route, canals can attract more shipping traffic, making them the preferred choice over alternative routes [45]. This can shift traffic patterns and enhance the competitiveness of ports connected by canals [46]. Canals can also promote trade activities. The Grand Canal connected neighboring markets, transporting an estimated 6 million piculs of grain trade each year [47]. The Suez Canal handles about 12 percent of world trade and if it were to close, this would likely result in a substantial shock to world trade [48]. Finally, canals generate huge revenue. Ship canals bring substantial revenue through tolls and navigation charges [49]. For instance, the Panama Canal's income is a significant contributor to Panama's GDP, highlighting its economic importance [50].

4. Wetland Hydrology

Wetland hydrology refers to wetland inflows, outflows, and interactions with other habitat factors, etc. [51], all of which profoundly influence wetland functions, biodiversity, and ecosystem services [52]. Hydrological elements such as wetland water level (or flow), frequency, period, and intensity are important indicators of wetland hydrology [53]. Studies on wetland hydrology influenced by ship canals can be categorized into two aspects: hydrological connectivity and hydrological elements.

4.1. Hydrological Connectivity

Hydrological connectivity can be divided into the longitudinal connectivity of rivers, lateral connectivity of riffle-channels, and vertical connectivity between surface water and groundwater [54]. Stepped ship locks are commonly installed as part of a canal and have the potential to cut off the wetland's longitudinal hydrological communication (Figure 4). Robinson et al. [55] quantified the wetland hydrological connectivity of the River Murray in southern Australia by a numerical model, which is regulated by six locks and weirs built for navigation. Under the regulated conditions (located with six locks and weirs), approximately 96% of the sampled wetland area was connected once every ten years; while under natural conditions (the locks and weirs were removed), around 90% of the sampled wetland area was connected each year.

Revetment construction and the widening of narrow rivers for canals may harm riparian zone vegetation and disrupt hydrological horizontal connections [56]. The traditional revetment structures hamper the water exchange between the bank and the river [57]. The shape, slope, subsurface features, and material of revetment influence water exchange and consequently near-shore water quality [58]. And using ecological revetment could benefit hydrological and biological connectivity, for example ecological pervious concrete [58,59].

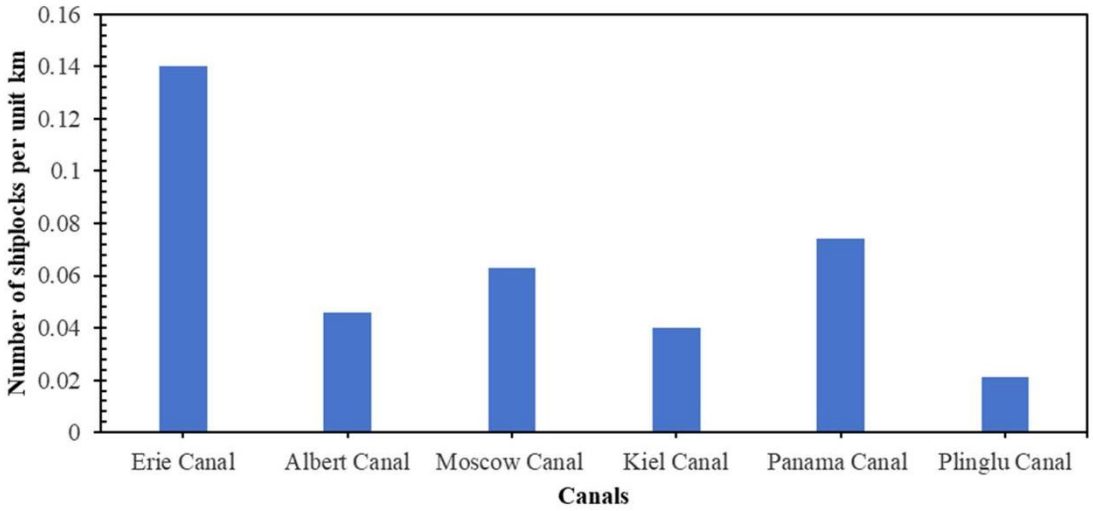


Figure 4. Number of ship locks per unit kilometer for six canals.

4.2. Hydrological Elements

4.2.1. Flow Volume

The flow volume in ship canals is different compared to natural waterways, which adds navigation water use [60]. The operation of ships crossing through locks results in the exchange of water between upstream and downstream [61]. Thus, ship canal streamflow is regulated partly according to the channel classes, ship numbers, and ship lock operation regulations. For example, the daily number of ships crossing the Kiel Canal is about 10 ships [44] and 51.7 ships for the Suez Canal [62]. Nearly 52 million gallons of fresh water are discharged daily into the Atlantic and Pacific oceans via the Panama Canal with 35–45 ships crossing [63]. The water diversion of the Pinglu Canal, which is under construction, is expected to be 35 m^3/s, assuming ship locks open 20 times per day [64]. The average daily water demand of the Ganyue Canal (in the planning stages) is estimated to be 11 m^3/s [65]. Due to the diversion of water resources for canal operations, the hydrological conditions of the wetland ecosystem along the canal would be altered [66,67]. In the simulation of the hydrological conditions of the Xinjiang River's cascade ship locks in China, Zhang et al. [68] discovered that following the installation of the locks, the monthly average flow in April, the breeding period for four major Chinese Carps, decreased by over 20%. Many canals implement water-saving ship locks to mitigate water usage [69].

4.2.2. Flow Exchange

Canals have reduced complicated flow exchange patterns. The Burlington Ship Canal, which connects Lake Ontario with Hamilton Harbour, was found to exhibit a two-layer hydraulic exchange flow, in which the lower water flows from the lake into the harbor and the upper flows in the opposite direction [70]. The same phenomenon was examined for the İstanbul Canal (in the planning stages) which may form the two-layer exchange between the Black Sea and the Marmara Sea via numerical simulation analysis [71]. The hydraulic simulation showed that the construction of the Nowy Swiat ship canal between the Vistula Lagoon and the Baltic Sea would not generate a major change in the Vistula Lagoon's water balance [72]. Flow exchange may not alter water balance, but instead promote the diffusion of pollutants which usually accompany the upper water [70].

4.2.3. Velocity

Although canal dredging would change the water velocity at the construction zone in river course [73], ship locks play a significant role in altering velocity. Typically designed for navigation, ship locks are arranged in a continuous series, creating a sequence of cascading pools rather than maintaining a flowing river [74]. When a ship lock is constructed, the water velocity is reduced and the impounded reach replaces lotic habitats with lentic

habitats [75]. A study regarding the German Basin, Serrig, indicated that 66.3% of the sub-daily variations in flow velocity are related to the ship lock [76]. The changes in flow velocity and water depth would impact the wetland ecosystem [77].

4.2.4. Water Level

The ship lock operation in canals should maintain the water level for navigation [78]. To maximize the use of hydroelectric power plants, which are suited in some ship locks, the number of locks is expected to increase [79]. A sudden increase or reduction in discharge caused by ship lock operations would induce water-level fluctuations, contributing to 45.4% of the sub-daily variations at Basin Serrig in Germany [76]. Meanwhile, in estuarine wetland areas, the non-constant flow caused by ship crossings may also result in serious fluctuation in water levels [80].

4.2.5. Climate Change Response

The effects of climate change on hydrological elements have been seen in recent years due to extreme weather, such as floods and drought [81]. And ship canals seem to be increasingly vulnerable to periods of flooding and drought [82]. Canals provide some flood storage to attenuate peak flows [83]. High water surface elevations during floods can hinder safe navigation, complicating vessel operations and increasing the risk of accidents [84]. Droughts can lower the base flow of the Albert Canal, impacting shipping operations and increasing salinity intrusion [85]. According to some climate scenarios, low water levels would reduce the transport capacity of waterway transport which experiences a severe restrictions on the load factor of ships [86].

Changes in wetland hydrology can affect various wetland elements and ecosystems. The existing literature mainly focuses on the macroscopic changes in water resources and hydrological conditions caused by canals. But there needs to be more research on the combined effects of climate change and canals on hydrological elements. And few studies have investigated the microscopic hydrological variations caused by ship locks, including either hydrological elements or processes. However, the discontinuous water flow generated by ships passing through locks will lead to more complex hydrological conditions in canals. Greater attention should be given to the temporal and spatial variations in hydrological processes generated by canal locks, especially during fish spawning periods and wetland distribution areas.

5. Wetland Pollutant

Water in canals often has poor circulation due to low velocity, which leads to poor quality, especially in dead-end areas, as it receives treated discharge and urban stormwater [87,88]. The effect of the canal on water quality is described in the following three aspects.

5.1. Nutrients Variation

The problem of eutrophication often occurs in ship canals, especially excessive phosphorus, as shown in Table 2. Firstly, the discharge of sewage water caused by ships in canal alleviates nutrient loading. For example, ship-generated water pollutants in the Shandong section of the Beijing–Hangzhou Canal are about 300 mg/L of COD, 120 mg/L of BOD_5, 200 mg/L of SS, and 30 mg/L of NH_3-N [89]. To effectively manage these pollutants, ports along navigable canals must develop appropriate reception facilities. Secondly, the entrance area of the ship lock is often regarded as a backflow area and a slow flow zone, causing sediment deposition [90]. Similar to research on hydroelectric dams, reservoirs have an interception effect on sediment and its particulate phosphorus, which can lead to a decrease in downstream nutrients [91]. However, some researchers argue that the view of nutrients decrease downstream overlooks the biogeochemical transformations of phosphorus within reservoirs, including the subsequent release and movement of bioavailable phosphorus [92]. Meanwhile, ship movements and ship lock operations may result in nutrient transfer through the canal [93]. In addition, water diversion and drainage lower

the nutrient level of the receiving body of water, thereby altering the structure of plankton communities [94–96]. According to the research results mentioned above, it can be inferred that the construction of canals (ship locks) and the application of navigation water diversion may modify the distribution of biogenic elements leading to ecological impacts.

Table 2. The water quality of ship canals.

Name	Water Quality Problem	Pollutant	Possible Reasons	Author [Ref.]
The East Zhejiang Canal	Eutrophication	Phosphorus	Wastewater discharges	Jin et al. [97]
The Kennet and Avon Canal	Eutrophication	Phosphorus	Effluent sources	Neal et al. [93]
The Grand Canal in Yangzhou	Eutrophication	Nitrogen	External loading	Huang et al. [98]
The Plinglu Canal	Salt intrusion	Salt	Channel deepening	Yi et al. [99]
The Ghent–Terneuzen Canal	Salt intrusion	Salt	Ship passing ship locks	Biemond et al. [100]
The Kiel Canal	Salt intrusion	Salt	Ship passing ship locks	Steinhagen et al. [101]
The Suez Canal	Salt intrusion	Salt	Ship passing ship locks	Abril and Abdel-Aal [102]
	Heavy mental pollution	Cd	Related to marine ships and vessels discharge	Shetaia et al. [103]
The Panama Canal	Heavy mental pollution	V, Sr and so on	Traffic vessels' maintenance and emissions	Valdelamar-Villegas et al. [104]
The canals of Aveiro	Heavy mental pollution	Cu, Pb, Zn and so on	Industrial discharges along the coast	Martins et al. [105]
The Begej Canal	Heavy mental pollution and carcinogen	Hg, Cr, Pb and so on, PAH dibenzo[a,h] anthracene,	Recipient of wastewater and run-off from the surrounding agricultural land during periods of heavy rain	Dubovina et al. [106]
The Chicago's Sanitary and Ship Canal	Carcinogen	PAHs and PCBs	Water reclamation plant effluent	Liang et al. [107], Peverly et al. [108]
The Amsterdam Canal	Microplastics		Wastewater treatment plants discharge	Leslie et al. [109]
The Hood Canal	Microplastics		/	Mahoney [110]
The South Jiangsu Canal	Microplastics		Wastewater treatment plants discharge	Jin et al. [111]

Thirdly, the significant discharge of domestic, agricultural, and industrial wastewater into canals is a major cause of water pollution. The monitoring results of water quality in the East Zhejiang Canal indicated that the canal was eutrophic, while phosphorus was the main driver of eutrophication [97]. Reducing wastewater discharges into the canal and setting up riparian zones effectively improve canal water quality.

5.2. Salt Intrusion

Canals that connect rivers with the sea or estuaries through ship locks can lead to significant saltwater intrusion [112]. With passing vessels, the ship lock transports saltwater into the freshwater [113]. Thus, canals could be considered as a transportation way for salt. For instance, the annual average net volume of salt from the Red Sea to the Mediterranean through the Suez Canal is estimated at about 20 ton/s [102]. Increases in

estuarine depth caused by canal regulation are a major factor influencing variations in salinity distribution [114]. The simulation on the saltwater intrusion in the Qinjiang River which is deepened for the Pinglu Canal in China showed that the saltwater could increase 5 km compared to the natural conditions during high tide [99]. Frequent lock openings to meet the increasing shipping demands have contributed to the extent of saltwater intrusion [115]. Meanwhile, the combination of rising sea levels and a reduction in upstream discharges in tidal rivers resulting from climate change would intensify saltwater intrusion, possibly threatening water quality, especially drinking water inlets in the canals [85].

5.3. Sediment Pollutants

Shipping is regarded as a significant source of heavy metals in canal sediment [116,117]. Shetaia et al. [103] investigated heavy metal levels in Bitter Lake, situated in the center of the Suez Canal. They found that most sampling sites had high-level ecological risks for Cd, and some samples with relatively high values of heavy metals may be related to marine ships and vessel discharge, most of which were located near the waterway. In the Panama Canal, heavy metal monitoring of sediments at 11 stations demonstrated that 36 percent of the stations had relatively high levels of heavy metal contamination with V, Li, Pb, and Sr [104]. The elevated lead levels were likely linked to maintenance and emissions from the vessels. Martins et al. [105] found a high concentration of heavy metal contamination (such as Al, Cd, Co, Cu, Fe, Pb, Mn, and Zn) in the canal sediments of Aveiro (Portugal) due to industrial discharges along the coast. Meanwhile, the depression wave from canal vessels would lead to sediment resuspension [118]. Dubovina et al. [106] mentioned that when navigation in the Begej Canal was suspended, the sediment accumulated rapidly and contamination occurred. Dredging and the depositing of sediments are performed regularly to remove sediment contaminants [119].

Sediment resuspension caused by successive vessel traffic can lead to the remobilization of contaminants [93]. It was found that ten vessel-induced wakes in Venice Lagoon of Italy could lead to suspended sediment concentration above 400 mg/L, 30 times higher than the average background [120]. However, a study on rivers in northern France indicated that sediment resuspension caused by navigation contributed little to dissolved metals and phosphorus of sediment in canals [121].

In some canals, polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) were detected, which is likely related to water reclamation plant effluent, rather than canals or shipping [107,108]. Nonetheless, the release of PAHs and PCBs should be a concern in the implementation of dredging projects to maintain navigation depths [122,123].

In addition, some canals are contaminated with microplastics [124]. In the Amsterdam Canal, the concentrations of microplastics ranged widely in different samplings, from no detection to over 10,000 particles/kg^2 dry sediment [109]. The concentration of microplastics varied from 0.080 pieces/m^3 in the Northern Hood Canal to 0.36 pieces/m^3 in the Southern Hood Canal [110]. The abundance of microplastics in the body of water in the South Jiangsu Canal ranges from 3.41 to 19.07 particles/L [111]. Wastewater treatment plants stand as significant contributors to microplastics in water [125]. Plastic is ultimately transported from land to sea via rivers, shipping, and airborne transfer [126].

We noticed that the existing research has already focused on the water quality issues of canals. However, there is relatively limited research on the diffusion of pollutants and changes in salinity resulting from ship activities in these canals. Further investigation is needed regarding the distribution of novel contaminants in the canal that could have an impact on human health, including endocrine disruptors, antibiotics, and persistent organic pollutants.

6. Wetland Botany

6.1. Dislocation and Biomass Loss

The construction and maintenance of canals could lead to wetland botanical loss. For example, canal dredging caused a wetland loss of about 4100 ha on the coast of

Louisiana [127]. Additionally, the waves generated by shipping within canals have a long-term impact on canal banks and riparian plants. Ship navigation becomes one of the energy inputs that influences a canal's initial hydrodynamic field [128]. In canals, as opposed to natural waterways, the impact of ship-induced waves and the ensuing hydrodynamic changes on the channel banks are more important [129]. Ship waves have replaced the bed-making effect of the natural river flow as the most important driving factor in its cross-section in navigable canals [130]. Changes in the morphology of the canal cross-section can cause vegetation inversion on both sides of the banks. The effects of ship-induced waves on plant slopes have been summarized into three main characteristics: (1) scouring of slopes by the water between the ship and the slopes; (2) spiral wave action formed by diffusion-wave at the stern of the ship and shear wave; (3) soil carried away by the ship waves as they climbed and fell down on the slopes [131]. For unconsolidated sandy alluvium, for instance, wave heights of 30 to 35 cm were shown to be the thresholds of wave-induced shoreline erosion; lowering wave heights below 30 cm by restricting boat speeds and minimizing boat crossings significantly reduced bank erosion [132]. Furthermore, waves caused by boat traffic might cause the water column to become more turbid, which may hurt the photosynthesis of wetland plants. However, research suggests that variations in water quality do not significantly affect plant health [133].

Under the influence of ship waves, vegetation on both sides of the canal experiences a decline in biomass. Ship-induced waves were shown to uproot macrophytes resulting in the reduction of plant biomass [37]. In situ observations have found that the composition and abundance of aquatic vegetation in British tourist canals are related to the height of cruise ships [134]. Simultaneously, the study of navigable river portions along the shore revealed that large speedboat-generated waves possess significant wave energy and often destroy the surrounding mudflat. This can hinder the natural evolution of mangrove habitats towards the periphery; excessive tidal flooding may cause degradation or impede the natural regeneration of wetland flora [135]. According to research on the Lancaster Canal, aquatic species do not survive in the waterway's main line when boat movements exceed 4000 my [136].

To cope with the impact of ship waves, plants have adopted various strategies according to their growth cycles [137]. For instance, seedlings often employ pressure-relieving methods to remain flexible and avoid breaking. With their strong stems, adult plants resist waves, displaying stress adaptation techniques. In addition, studies conducted indoors have shown that plants impacted by waves also direct more biomass toward their roots, improving their ability to regulate the soil and withstand the effects of waves [138].

6.2. Biodiversity Decreased

The primary cause of indirect consequences is the salt and flow stress induced by canals, which alter hydrodynamics and the distribution of water resources, leading to a reduction in biological diversity among wetland plants [139]. Several variables, including salinity, water level gradient, frequency and cycle of floods, and others can influence wetland vegetation development and distribution features [140]. In less dynamic parts of the backwaters of canals, due to high turbidity and sediment accumulation, it is difficult to develop rooting submerged macrophytes [141]. It is demonstrated that a variety of factors, including species invasion, salinity stress, and deforestation, related to the Panama Canal's construction and navigation have contributed to Lake Gatong's gradual transition from a swamp-type environment towards a more saline lake-governed system [142].

The networks of shipping canals, coupled with water transfers for navigation, may act as a pathway for plant invasion [143]. *Hydrilla verticillata*, a Eurasian aquatic plant that might have been introduced in ballast water, was the typical plant fragment in the Panama Canal lock that washed in from Gatun Lake [144]. A total of 52 of the 72 maritime plant species had never been observed in the Suez Canal before in Lipkin [145] study. According to trend analysis, shipping accounts for 48% of foreign macroalgal immigration to Greek beaches, with progressive immigration through the Suez Canal coming in second

(33%) [146]. Invasions can decrease the spread of native communities through interspecific competition, thus considered one of the major causes of biodiversity loss [147,148].

Based on the literature review, most studies on the effects on botany have centered on riparian vegetation. There are few studies about the effects on phytoplankton and aquatic botany caused by canals. In addition, there is insufficient research on the long-term succession of wetland vegetation and biodiversity variation due to ship waves, salinity, flow stress, and flora invasion caused by canals. The changes in ecosystem function, structure, and processes under canal stress deserve in-depth research.

7. Wetland Animal

7.1. Biomass Reduction

Canal construction and operation may lead to ecological losses. Zhang et al. [149] estimated that 7100 tons of benthic invertebrates, fish eggs, and fingerlings would be directly lost resulting from waterway dredging and reef cleaning for the construction of ship locks in the Pinglu Canal. However, benthic organisms may recover to their original levels over time through natural self-recovery [150]. In the process of canal operation, ships can collide with aquatic organisms, even causing them harm [151]. Field experiments by Gabel et al. [152] revealed that ships traveling at 11 km/h and 35 m from the shore displaced 45% of the invertebrates from their natural habitats.

7.2. Habitat Loss

Multiple ship lock cascades would change the original surroundings, leading to habitat fragmentation. The ship locks installed in the canal could block the migration of aquatic organisms. Verhelst et al. [153] investigated the barrier effect of locks on fishes and found that only one-third of the 70 tagged European silver eels could pass through the locks, and their speed of passage was very slow. However, navigation locks could be an option for fishes to pass an obstacle at dams, especially low-head dams [154,155]. Some studies even found that the navigation locks perform better for fish passage than fishways [156]. Nevertheless, Tao et al. [157] believed that the fishes' behavior across a navigation lock was general rather than indicating that the fishes regarded the ship lock as a passageway.

The operation of ship locks would increasingly change the original habitat of canals. Water transportation for navigation would modify the distribution of sediment and nutrients, which affects plankton, benthic organisms, and fishes [37]. Locks reduce water flow in channels and may increase the number of zooplankton species [158,159]. For example, rotifers seem to dominate over crustaceans in diversity and density at the Bydgoszcz Canal and the Noteć Canal [160]. Morton [161] also found macrobiotic carnivores occurred less frequently in canals than in rivers and suggested that the practice of canal developments in narrow-mouthed estuary rivers is considered to be detrimental to adjacent fish populations.

Shipping activities increase underwater noise, negatively impacting aquatic activity [38,162]. However, different kinds of fishes presented different adaptions to canals and vessel traffic. In a study conducted by Wolter [163] in the Mtiritz–Elde–Wasserstrage (MEW) Canal, the relative abundance of pike in canals was slightly lower than that of the natural river, but no significant differences in other fish abundance and species diversity. It was indicated that fish abundance might increase while body size decreases in canals with high shipping traffic [164]. However, roach was found to be tolerant of river channelization and high vessel traffic in the Shropshire Union Canal [165].

7.3. Non-Native Species Invasion

Canals crossing different basins cause biological invasions, as shown in Table 3. The canals between rivers may greatly facilitate the exchange of aquatic fauna [166], resulting in a loss of biodiversity [167]. Shipping activities in canals are considered a major factor in the introduction of non-indigenous species [148]. Since the construction of the Panama Canal, schizopods have been migrating and spreading through the canal, and studies have speculated that ballast water from ships as well as fouling of ships may have

led to biological migration and species invasions [168]. Zakaria [169] conducted a study on the migration of zooplankton from the Red Sea to the Mediterranean Sea through the Suez Canal, as the salinity of the Red Sea is slightly higher than that of the Mediterranean Sea. Before 1900, 22 non-indigenous species were recorded in the Mediterranean and 11 of them had entered the sea through the Suez Canal [170]. Interestingly, while ship noise in navigation locks negatively impacts fishes, it may reduce the rate of biological invasion by fishes [171].

Table 3. Non-native species invasion in canals estimated by the existing major research.

Name	Invasion Species	Author [Ref.]
The Panama Canal	Schizopods	Ros et al. [168]
The Suez Canal	Zooplankton	Zakaria [169]
	Ascidians	Rius and Shenkar [172]
The Chicago Sanitary and Ship Canal	Fishes (*Hypophthalmichthys nobilis* and *Hypophthalmichthys molitrix*)	Moy [173]
Canals connecting to river Elbe	Macrozoobenthos	Nehring [174]
The Rhine–Main–Danube Canal	Fishes	Hanafiah et al. [175]
The Central Arizona Project canal	Fishes	Clarkson [176]
The Volga–Don Canal	Benthic foulers, macrophytes, zooplankton	Shiganova et al. [177]
The Welland Canal	Fishes	Kim and Mandrak [178]

From the literature review, it is found that the problem of biological invasion in canals is the focus of more attention from scholars in various countries. Few studies were conducted on birds, migration blocking, or habitat reduction in canals. Moreover, many of the effects of canal construction on wetland animals occur gradually over several generations, and there are a lack of observational and research data on long-term impacts.

8. Potential Mitigation Strategies

8.1. Design and Construction Phase

Firstly, an independent environmental impact assessment should be conducted prior to canal construction [16]. In the process of designing and selecting the route for canal engineering, it is necessary to make a mandatory selection of the route and prioritize the option that occupies less wetland space [11]. Secondly, hydrological variability caused by canals is the primary driver of environmental and ecological impact. Many projects have adopted ecological bank protection and fishways to mitigate the obstacles to hydrological connectivity [59,154]. Thirdly, improving ecological and environmental infrastructure along the canal is essential. For instance, installing ship pollutant-receiving facilities along the canal can effectively address the issue of waste generated by ships. Using electric barrier systems in the ship locks of canals could prevent the inter-basin movement of aquatic nuisance species between different basins [179]. Barriers such as air curtains or bubble screens can be installed in the canal or at lock entrances to mitigate saltwater intrusion [115,180].

8.2. Operational Phase

First of all, reducing vessel speeds and increasing the distance between the successive ships are the measures required to reduce ship-induced waves and their negative effects [118]. Secondly, based on the ecological needs of wetlands, ecological scheduling is adopted through ship locks to solve the ecological problems caused by canals, such as salinity invasion [92]. Thirdly, controlling external inputs by reducing urban and industrial wastewater discharges into the canal can lower pollution loads. Fourthly, ecological restoration of wetlands around the canal could be undertaken. For example, after dredging in the narrow area along the waterway, collecting parts of surface sediment layers as propagule banks may be a way to enhance re-vegetation [181].

9. Conclusions

9.1. Summary

Ship canals have been extremely significant for developing trade and transportation since ancient times. They can lower transportation costs, enhance the competitiveness of ports, and bring substantial revenue. A number of nations have also proposed planning for the building of canals to consider economic and geographical aspects. The scale, cross-section, and morphology of rivers are frequently altered by canals, which also have a profound and wide-ranging impact on wetlands. Ship canals also serve as a means of communication between various water systems (sea regions). Consequently, research should be focused on the manner and extent of coercion that canals exert on different elements of wetland ecosystems, as well as the resulting changes in ecosystem structure, function, and diversity.

Established studies indicate that canal projects alter the hydrological processes of wetlands, degrade water quality, eliminate wetland vegetation, disrupt wildlife, and increase ecological risks, as shown in Table 4. The cumulative effects of the aforementioned effects on the wetland ecosystems will either alter the pattern of ecological succession or result in localized ecological degradation. Based on the existing literature, the greatest impact of canals on wetland ecology is the invasion of organisms, leading to a decrease in biodiversity. Because of this, the canal's effects on wetlands are now taken seriously when making project decisions. The economic and social benefits and the environmental costs created by canals should be clearly considered. Measures must be taken in all directions to minimize and make up for the environmental damage during the canal's development and operation.

Table 4. The ecological effects of canals on wetlands.

Impact Category			Impact and Consequences
Hydrological process	Hydrological connectivity		Stepped ship locks cut off wetland's longitudinal hydrological connectivity. The revetment construction and widening of narrow rivers may disrupt hydrological horizontal connections.
	Hydrological elements	Flow volume	The streamflow in ship canals is regulated partly according to the channel classes, ship flows, and ship lock operation regulations.
		Flow exchange	Canals would reduce a two-layer hydraulic exchange flow.
		Velocity	Between ship locks, the water velocity was reduced, and the impounded reach was replaced lotic habitats with lentic habitats.
		Water level	A sudden increase or reduction in discharge during ship lock operations would induce water-level fluctuations.
		Climate change response	High water surface elevations during floods can hinder safe navigation. Low water levels during a drought would reduce the transport capacity of waterway transport.

Table 4. *Cont.*

	Impact Category	Impact and Consequences
Pollutant process	Nutrients	The problem of eutrophication often occurs in ship canals. Ships discharge polluted water. Large amounts of domestic, agricultural, and industrial wastewater are discharged into the canal.
	Salt intrusion	Canals connecting rivers and the sea or estuaries by ship locks would lead to serious saltwater intrusion.
	Sediment pollutants	Heavy metals, PAHs, PCBs, and microplastics are detected in canal water and sediment.
Botany	Dislocation and biomass loss	Ship-induced waves lead to wetland botany dislocation and biomass loss.
	Biodiversity decreased	The primary cause of indirect consequences is the salt and flow stress caused by canals which change hydrodynamics and distribution of water resources, causing biological diversity reduction in the plants of wetlands.
Animal	Biomass reduction	Ecological losses occur as a result of canal construction and operation. Ships can collide with aquatic organisms.
	Habitat loss	Multiple ship lock cascades would change the original surroundings, leading to habitat fragmentation. Shipping activities increase underwater noise and have a negative impact on aquatic activity.
	Biological invasion	Cross-basin canals may cause biological invasion via river connection and shipping.

9.2. Future Research Prospects

A survey of previous research indicates that canals primarily impact wetland ecology through modifications to their natural habitats and hydrological conditions, as well as through direct or indirect disturbances to flora and fauna. To provide a research foundation and support for governmental decision-making on new canals and the formulation of protection measures for large-scale canal projects, it will be necessary further to strengthen research on canal-related wetland protection in the future. Based on the above reviews, the following is recommended for future research.

Firstly, the effects of canals on wetland ecosystems are complex and long-term. It is necessary to conduct in-depth research on the mechanisms by which canals impact wetlands through in situ observations, indoor experiments, and model simulations. Ecological thresholds could be established based on the findings of the ecological observation of canals. Secondly, greater attention should be given to the impacts of ship navigation and the ship lock operation on hydrological elements, water quality, aquatic plants, and wetland animals. Thirdly, research should be conducted to assess the impact of river networks formed by canals on wetland ecosystems. Fourthly, further studies are needed on ecological scheduling, ship speed reduction, and other mitigation strategies for the protection of wetlands. Lastly, developing a green canal assessment system could be beneficial in evaluating the disruption and coercive impacts of canals on wetland ecosystems.

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