

Historical, Economical and Environmental Impacts of Suez Canal Connecting the Mediterranean Sea and Red Sea

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Abstract

The Suez Canal is a unique sea-level waterway between northern Africa and southern Asia that connects the Mediterranean Sea to the Red Sea via the Isthmus of Suez. The canal's artificial navigation route substantially reduced the sailing distance between countries in Europe and East Asia and offered a more direct route between the North Atlantic Ocean and the Indian Ocean through the Mediterranean Sea and the Red Sea. The primary objective of this study is to document the historical, economical, and environmental impacts of connecting the Mediterranean Sea and the Red Sea via a canal. After the completion of the Suez Canal in 1869 the canal became an economically lifeline for Egypt. However, the economic gains were partially offset by negative environmental impacts. The impact of port activities on the environment depends on their cargo volume and location, seaports can have an impact on the air quality and therefore on the health of the communities along the Suez Canal. The salinity barrier to migration was removed and animals and plants from the Red Sea began colonizing the eastern Mediterranean. Since the 1880s, species from the Indo-Pacific Ocean have been introduced, via the canal, into the Mediterranean ecosystem. They are endangering some local and endemic species and impacting the ecology. The results showed significant changes in the shoreline and land cover due to climate change and anthropogenic activities that necessitate the implementation of adequate protective measures. The findings of this study may assist policymakers in formulating adaptation plans to protect this crucial area, the communities along the Suez Canal and the Red Sea and Mediterranean ports, from climate change and human activities.

Keywords

Suez Canal, Egypt, Mediterranean Sea, Red Sea

1. Introduction

The Suez Canal is one of the three most important international canals in the world. The other two are the Panama Canal in Central America and Welland Canal on the St. Lawrence Seaway between Canada and the United States. The major difference is that the Suez Canal does not require locks and dams since the Red Sea and the Mediterranean Sea are at the same elevation. It is important to learn and know about the Panama and Welland canals and their environmental impacts. Hopefully, historical lessons learned can be applied to the Suez Canal to help mitigate the adverse environmental impacts.

1.1. Case Study: Panama Canal

The Panama Canal [1] linked the Pacific and Atlantic coast ecosystems and destroyed a natural barrier, the Isthmus of Panama, by connecting of the two oceans, creating Lake Gatun on the Chagres River, covering up fertile agricultural lands and swamps. During the Panama Canal construction phase, many workers died from tropical diseases including malaria and yellow fever. To reduce the mosquito population, malathion was sprayed at the canal construction site since the 1960s. Malathion has a relatively short half-life and does not appear to degrade into other environmentally harmful by-products. After the damming of the Chagres River to create the Lake Gatun for the Panama Canal, floating plants, including hyacinth started to clog the flow of the water through Lake Gatun. A mixture of white arsenic, soda and water was sprayed from 1913 to 1930s from boats on the floating vegetation. The arsenic, which has no half-life and is water soluble, was deposited in Lake Gatun waters and sediments. The primary source of drinking water for Panamanians is Lake Gatun.

1.2. Case Study: Welland Canal on the St. Lawrence Seaway

Lake Erie drains into Lake Ontario, via the Niagara River, but the river was not navigable due to the obstacles of Niagara Falls and the Niagara Escarpment [2]. Until the 1820s ships could not travel into Lake Erie. It was not possible to engineer a bypass of Niagara Falls with a series of locks due to the 100 m high Niagara escarpment. This escarpment obstacle to Niagara River navigation was overcome in 1829 with the completion of the first of four Welland Canals with locks 40 kilometers west of the Niagara River through the glacial till and alluvium that overlays the Niagara Escarpment. This permitted ocean-going ships to enter Lake Erie and to continue to Lake Michigan, Lake Huron and Lake Superior. The Eastern Great Lake shorelines, riverbanks and canals are actively eroding because of high surface water levels and flooding. The settlement of millions of people into the Eastern Great Lakes via the NYS Barge Canal and St. Lawrence Seaway migration pathways have created environmental and natural resource risks and challenges. These challenges and risks include deterioration of the Fourth Welland Canal and the need to replace it with the Fifth Welland Canal, industrial and urban wastewater disposal, shoreline, riverbank and erosion as results of high-water levels, the building of structures on the shoreline banks, invasive species and flooding.

1.3. Case Study: Suez Canal

Between 1859 and 1869, the Suez Canal was owned by the government of Egypt and excavated and managed by the Suez Canal Authority. From its completion in 1869 to August 2015, the canal serves over 50 ships or vessels a day and is a critical shipping artery. The Suez Canal was too narrow a waterway to serve two-way traffic. Ships, in convoys, passed through the canal. It took a ship between 12 - 16 hours to pass through the canal. Since the 2014 expansion project, the canal allows only regulated two-way traffic executed in shifts. The Suez Canal connects northern Africa and southern Asia, via the Isthmus of Suez, from the Mediterranean Sea to the Red Sea. The canal's opening allowed the first salt-water flow between the Mediterranean Sea and the Red Sea. The construction of the Aswan High Dam across the Nile blocked the naturally nutrient-rich silt entering the eastern Mediterranean at the Nile Delta and reduced the inflow of freshwater. Since the 1880s, exotic species from the Indo-Pacific Ocean were introduced into the Mediterranean via the canal and have become a significant component of the Mediterranean ecosystem. They endangered some local and endemic species and impacted the ecology. The primary objective of this study is to document the historical, economical, and environmental impacts of connecting the Mediterranean Sea and the Red Sea via a canal. Animals and plants from the Red Sea began colonizing the eastern Mediterranean after the salinity barrier to migration was removed.

2. Study Site—Physical Setting and Cultural History

2.1. Natural Resources

The land bridge between Asia and Africa is called the Isthmus of Suez. Both continents are old (formed 66 to 2.6 million years ago) while the land bridge is rather young (2.6 million years to 11,700 years ago). In the Pliocene, the isthmus of Suez became fully lifted and connection to the Mediterranean was permanently severed. The land bridge created by sea level changes exposed the isthmus that broadened northward into a low-lying coastal plain [3]. Initially, the Nile delta at that time was located 15 km farther to the east of the current Suez Canal outlet to the Mediterranean Sea.

The isthmus is composed of sand, marine sediments, gravel, and coarse deposited during periods of high rainfall. The Nile alluvium is the parent material on the northern end of the canal and the southern end is composed of windblown sand [4]. There are three shallow water-filled Lakes with lacustrine deposits and a few more resistant bands of gypsum and limestone at the south end of the isthmus. Since most of the parent material is unconsolidated alluvium and windblown sand, it was necessary to use stone, cement, and steel pilings for stabilizing the erosive stream banks.

2.2. Water Bodies and Biodiversity

In extra-arid climates, availability and quality of water plays a major role in

regulating biotic conditions and ecosystem diversity. The Suez Canal has become a major hydraulic structure that is not only an artificial aquatic habitat but also connects several aquatic and near-water ecosystems that initially have been quite different in origin and ecological status.

The Gulf of Suez is a distinct semi-enclosed region of the Red Sea with an elongated shape stretching over 290 km that follows the underlying geologic fault—a northern element of the Red Sea rift zone. The Gulf's water mass is relatively shallow (average depth of 40 - 50 m) and vertically mixed throughout the year, with well-developed latitudinal gradients in temperature and salinity. The Gulf has distinct assemblages of reef-based communities, but most parts of its seascape have no national or internationally recognized protection status (the southern part of the Canal along with the coasts of Suez Bay, the northernmost section of the Gulf of Suez, and the adjoining land are qualified in 1999 as Suez Important Bird & Biodiversity Area¹).

The Nile Delta Fan of the Eastern Mediterranean Sea is also ecologically unique and, in this case, internationally recognized with EBSA status². Thanks to a favorable combination of geological features (including bottom configuration and highly active seeps) and Nile silt sedimentation, this water area became home to endangered ecosystems composed of deep-sea corals, endemic polychaetae and mollusks species, and pelagic communities.

Manzala and Malaha coastal lagoons, both located along the NE edge of Nile Delta and opening to the Mediterranean Sea, are the largest and the most productive lakes of Egypt with a very specific and sensitive environment. Previously a single entity, they were divided by the Suez Canal in 19th Century and further reduced and fragmented by construction of the Port Said bypass in the 1980s and other developments. Most affected by contamination from drainage and other wastewater discharges, these wetlands have been transformed from a largely estuarine or marine environment to a brackish eutrophic water system³. Now they have both national (within Ashtum El Gamel Marine Protected Area established in 1998) and internationally recognized (as Lake Manzala Important Bird & Biodiversity Area since 1999 and the larger Lake Manzala and Lake Malaha Key Biodiversity Area since 2017⁴) protection status and are the subject of engineering improvements including those providing more effective conservation of the

¹BirdLife International (2024) Important Bird Area factsheet: Suez (Egypt). Downloaded from <https://datazone.birdlife.org/site/factsheet/suez-iba-egypt> on 15/10/2024.

²Ecologically or Biologically Significant Marine Areas identified on the basis of scientific criteria within the framework of the UN Convention on Biological Diversity (<https://www.cbd.int/ebsa/>).

³Thompson J.R., *et al.* Hydrological characteristics of three North African coastal lagoons: insights from the MELMARINA project//Hydrobiologia. 19 January 2009. P. 45-84.

⁴BirdLife International (2024) The World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Re:wild, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, World Wildlife Fund and Wildlife Conservation Society. <https://www.keybiodiversityareas.org/>.

adjoining Mediterranean seascape⁵.

2.3. Cultural and Historical Attempts to Create Isthmus of Suez Canals

The oldest predecessors of the Suez Canal which also connected the Red Sea with the Mediterranean but through the Pelusian arm of the Nile Delta are the so-called Pharaonic Canals built presumably in the 13th century BC and subsequently operated with interruptions and reconstructions until 767 AD.

Rappoport [5] believed “*that the Red Sea gradually receded over the centuries [6]. Coupled with persistent accumulations of Nile Delta silt, maintenance and repair of Ptolemy’s canal became increasingly cumbersome over each passing century. Al-Hakim bi-Amr Allah is claimed to have repaired the Cairo to Red Sea passageway, but only briefly, circa 1000 CE, as it soon ‘became choked with sand’ However, parts of this canal continued to fill with water during the Nile’s annual inundations*”.

Bartolomeu Dias opened a direct maritime trading route to India and the Spice Islands forever changed the balance of Mediterranean trade by the successful 1488 navigation of southern Africa. The former spice trading center of Venice was one of the most prominent losers in the new order. Venetian leaders, driven to desperation, contemplated digging a waterway between the Red Sea and the Nile. They anticipated the Suez Canal by almost 400 years to bring the luxury trade back to their doors again. However, this never happened.

Hassan and Tassie [7] noted “*During the 16th century, the Ottoman Grand Vizier Sokollu Mehmed Pasha attempted to construct a canal connecting the Red Sea and the Mediterranean. This was motivated by a desire to connect Constantinople to the pilgrimage and trade routes of the Indian Ocean, as well as by strategic concerns—as the European presence in the Indian Ocean was growing. Ottoman mercantile and strategic interests were increasingly challenged, and the Sublime Porte was increasingly pressed to assert its position. A navigable canal would allow the Ottoman Navy to connect its Red Sea, Black Sea, and Mediterranean fleets [8]. However, this project was deemed too expensive and was never completed*”.

Hall [9] suggested “*During the French campaign in Egypt and Syria in late 1798, Napoleon expressed interest in finding the remnants of an ancient waterway passage. This culminated in a cadre of archaeologists, scientists, cartographers, and engineers scouring northern Egypt [10]. Their findings, recorded in the Description de l’Égypte, included detailed maps that depict the discovery of an ancient canal [11] extending northward from the Red Sea and then westward toward the Nile*”.

Breasted [12] determined that “*Napoleon, who became the French Emperor in 1804, contemplated the construction of a north-south canal to connect the*

⁵Improving water quality in Lake Manzala (English). Washington, D.C.: World Bank Group. <http://documents.worldbank.org/curated/en/391431468025733822/Improving-water-quality-in-Lake-Manzala>.

Mediterranean with the Red Sea. However, the plan was abandoned because it incorrectly concluded that the waterway would require locks to operate, the construction of which would be costly and time-consuming. The need for locks was based on the erroneous belief that the Red Sea was 8.5 m higher than the Mediterranean as a result of fragmentary survey measurements collected in wartime during Napoleon's Egyptian Expedition".

The French conducted the first isthmus survey between 1798 and 1801 [2]. Studies for an Isthmus of Suez canal were made again in 1834 and 1846. Ortega [13] found "*Despite the construction challenges because of the alleged difference in sea levels, the idea of finding a shorter route to the east remained alive. In 1830, General Francis Chesney submitted a report to the British government that stated that there was no difference in elevation and that the Suez Canal was feasible, but his report received no further attention. Lieutenant Waghorn [14] established his 'Overland Route', which transported post and passengers to India via Egypt*".

"*Linant de Bellefonds, a French explorer of Egypt, became chief engineer of Egypt's Public Works. In addition to his normal duties, he surveyed the Isthmus of Suez and made plans for the Suez Canal. French Saint-Simonianists showed an interest in the canal and in 1833, Barthélemy Prosper Enfantin tried to draw Muhammad Ali's attention to the canal but was unsuccessful. Alois Negrelli, the Italian-Austrian railroad pioneer, became interested in the idea in 1836.*"

"*In 1846, Prosper Enfantin's Société d'Études du Canal de Suez invited a number of experts, among them Robert Stephenson, and Negrelli and Paul-Adrien Bourdaloue to study the feasibility of the Suez Canal (with the assistance of Linant de Bellefonds). Bourdaloue's survey of the isthmus was the first generally accepted evidence that there was no practical difference in altitude between the two seas. Britain, however, feared that a canal open to everyone might interfere with its India trade and therefore preferred a connection by train from Alexandria via Cairo to Suez, which Stephenson eventually built*" [13].

Plon [15] noted "*In 1854 and 1856, Ferdinand de Lesseps obtained a concession from Sa'id Pasha, the Khedive of Egypt and Sudan, to create a company to construct a canal open to ships of all nations. The company was to operate the canal for 99 years from its opening date. De Lesseps had used his friendly relationship with Sa'id, which he had developed while he was a French diplomat in the 1830s. As stipulated in the concessions, de Lesseps convened the International Commission for the piercing of the isthmus of Suez (Commission Internationale pour le percement de l'isthme de Suez) consisting of 13 experts from seven countries, among them John Robinson McClean, later President of the Institution of Civil Engineers in London, and again Negrelli, to examine the plans developed by Linant de Bellefonds, and to advise on the feasibility of and the best route for the canal. After surveys and analyses in Egypt and discussions in Paris on various aspects of the canal, where many of Negrelli's ideas prevailed, the commission produced a unanimous report in December 1856 containing a detailed description of the canal complete with plans and profiles. The Suez Canal Company (Compagnie*

universelle du canal maritime de Suez) came into being on 15 December 1858”.

3. Results

3.1. The Suez Canal

Suez Canal Company began canal construction in 1859 and completed it in 1869. At first, using baskets and picks, the digging was done with peasants utilized as forced labor (**Figure 1**). Later, steam shovels and dredgers operated by European laborers took over. Since dry excavation was more expensive than dredging the canal was anthropically flooded and dredged wherever possible. The entire canal was dug almost entirely through sand or alluvium. There were only a few locations where bedrock was encountered.

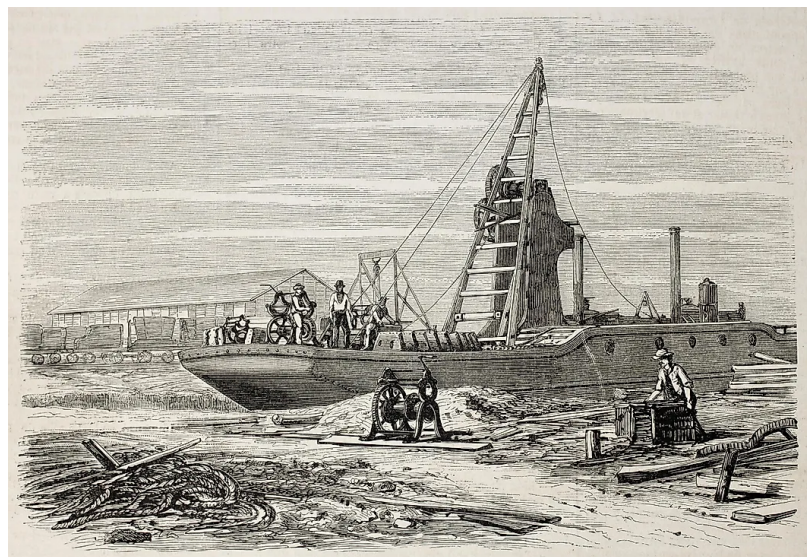


Figure 1. Digging Suez Canal [3].

The original canal (**Figure 2**), opened in 1869, was 8 m deep, 22 m wide at the bottom, and 61 to 91 m wide at the surface. The excavation, dredging, and disposal of 74 million m³ of sediment was required. The narrow channel resulted in 3000 groundings (**Figure 3**) by 1884. By the 1960s, there was a series of widenings to a minimum of 55 m width with a depth of 12 m at low tide [4]. In 1967 the canal was blocked during the Arab-Israeli War. In 2015, the Egyptian government finished a \$8.5 billion project upgrade of the canal. Approximately 29 km of canal was added to the original length.

The sea-level waterway running south-north across the Isthmus of Suez in Egypt, which connects the Red Sea and the Mediterranean Sea, is called the Suez Canal (**Figure 4**). The canal is 193 km long and located between Suez in the south and Port Said in the north. The shortest possible route would have been 175 km long. However, the canal connects a series of lakes. The Nile River Delta [16] is located west of the Suez Canal. The Suez Canal is east of the Sinai Peninsula (**Figure 5**). The canal, a continental boundary, separates Asia from Africa.



Figure 2. Suez Canal from the Mediterranean Sea to the Gulf of Suez [3].



Figure 3. The cargo ship is stuck on canal bank. Photo Credit: hindustantimes.com.

The Suez Canal Company was incorporated as an Egyptian joint-stock company headquartered in Paris, France [4]. Sa'ïd Pasha owned 44 percent and the French bought 52 percent of the shares. Representatives from 14 countries were on the first board of directors. In 1956, the canal was nationalized by Egyptian President Gamal Abdel Nasser (Figure 6). This was 13 years before the concession was due to expire causing the Suez Crisis. Since the Suez Crisis, the Egyptian government, via its Suez Canal Authority (SCA), has had complete control of the canal.

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Figure 6. President Gamal Abdel Nasser. In public domain. Photo Credit: les-yeux-du-monde.fr.

Kinross [17] reported “*The British government had opposed the project from the outset to its completion. The British favored the status quo since they controlled the Cape and the Overland routes to the Far East and India. The canal might have disrupted their commercial and maritime supremacy. Lord Palmerston, the project’s most unwavering foe, confessed in the mid-1850s the real motive behind his opposition: that Britain’s commercial and maritime relations would be overthrown by the opening of a new route, open to all nations, and thus deprive his country of its present exclusive advantages [18]. One of the British diplomatic moves against the project was to be disapproved for the use of ‘forced labor’ for the construction of the canal. Involuntary labor on the project ceased, and the viceroy condemned the corvée, halting the project*”.

Stanford [19] found “*International opinion was initially skeptical, and shares of the Suez Canal Company did not sell well overseas. Britain, Austria, and Russia did not buy a significant number of shares. With assistance from the Cattai banking family and their relationship with James de Rothschild of the French House of Rothschild bonds and shares were successfully promoted in France and other*

parts of Europe. All French shares were quickly sold in France. A contemporary British skeptic [20] claimed “*One thing is sure...our local merchant community doesn't pay practical attention at all to this grand work, and it is legitimate to doubt that the canal's receipts...could ever be sufficient to recover its maintenance fee. It will never become a large ship's accessible way in any case*”.

The Suez Canal is a unique sea-level waterway between northern Africa and southern Asia that connects the Mediterranean Sea to the Red Sea via the Isthmus of Suez (Figure 7). The canal's artificial navigation route substantially reduced the sailing distance between countries in Europe and East Asia (Figure 8). The route between the North Atlantic Ocean and the Indian Ocean, through the Mediterranean Sea and the Red Sea, was more direct.

The canal was built to serve international trade and for profit (Figure 9). For many years its international status remained in doubt [3]. In 1888 all the major maritime powers except Great Britain signed the Convention of Constantinople. The convention declared that the canal should be open to all ships of all nations in times of war and peace. In addition, the convention forbade acts of hostility in the canal waters and the construction of fortifications on its banks. Great Britain signed the convention in 1904.



Figure 7. The Middle East [4].

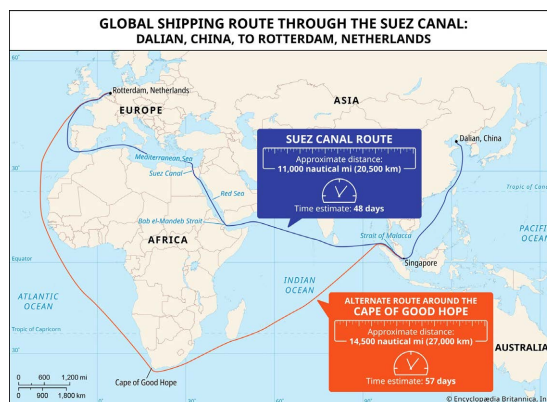


Figure 8. Global Shipping route through Suez Canal. From Dalian, China to Rotterdam, Netherlands [3].



Figure 9. Ships in convoys on Suez Canal [3].

Fisher and Smith [4] found “*The history of international use of the canal during wartime included the denial of passage to Spanish warships during the Spanish-American War of 1898. Permission of passage was denied for a squadron of the Russian navy during the Russo-Japanese War in 1905 and for Italian vessels during Italy’s invasion of Ethiopia in 1935-36 [21]. Theoretically, the canal was open to all belligerents during World Wars I and II, but the naval and military superiority of the Allied forces denied effective use of the canal to the shipping of Germany and its allies*”.

“*Following the armistice between Israel and its Arab opponents in 1949, Egypt denied the use of the canal to Israel and all ships trading with Israel. The first of two canal closings occurred during the Suez Crisis of 1956-57 after Israel attacked Egyptian forces, and French and British troops occupied part of the canal zone. Several ships were trapped within the canal during that blockade and were unable to leave until the north end was reopened in January 1957. The second closing was a consequence of the Arab-Israeli of June 1967, during and after which the canal was the scene of much fighting between Egypt and Israel. For several years the canal formed the front line between the two armies. Egypt physically barricaded both ends of the canal, and 15 ships, known as the ‘Yellow Fleet’ for the desert sand they slowly accumulated, were trapped in the canal’s Great Bitter Lake (Figure 2) for the entire duration of the war. The international crews of the anchored ships provided each other with camaraderie and mutual support. By 1969 most of the crew members had been allowed to leave. With the reopening of the canal in June 1975 and the signing of a peace treaty between Egypt and Israel in 1979, all ships (including those of Israeli registration) again had access to the waterway. Only 2 of the 15 trapped vessels were able to leave under their power*” [4].

Fisher and Smith [4] noted “*The Suez Canal extends from Port Tewfik in Suez City to Port Said in northeast Egypt. At the time of its opening in 1869, the canal was 164 km long. However, several enlargements and developments have increased the canal’s total length by about 30 to 193 km. It is 205 m wide and 24 m*

deep. Although the Suez Canal can handle larger ships and more traffic most canals can only allow passage of water vessels of up to 240,000 tons deadweight or 20 m draft. The ships or vessels must also not exceed 68 m in height above the water surface and a beam of 77.5 m (width at the widest point). Supertankers and larger ships can reduce their drafts by offloading their cargo onto smaller cargo ships owned by the Suez Canal Authority and reloading once they have transited the canal’.

The Suez Canal was a narrow waterway that could not serve two-way traffic from its inauguration in 1869 to August 2015 [3]. Using bypasses, including Tinsah, Ballah, Port Said, and Deversoir, ships in convoys passed through the canal in 12 - 16 hours. After the 2014 expansion project, the canal now only handles two-way traffic that is executed in shifts. When ships are still at least 24 km away from the Safe Water Mark and approaching the canal, they must radio the harbor. The southbound convoy departs at 3:30 AM from Port Said and the northbound convoy departs at 4:00 AM from Suez. This way, when the two convoys meet in the canal, they will be in the section that has been widened to allow two-way traffic [4].

For the express purpose of building the canal, Ferdinand de Lesseps formed the Suez Canal Company in 1858. Construction of the canal lasted from 1859 to 1869 and was officially opened on 17 November 1869 [21]. It offers vessels a direct route between the North Atlantic and Northern Indian Oceans via the Mediterranean Sea and the Red Sea. Avoiding the South Atlantic and Southern Indian Oceans reduced the journey distance by 8,900 kilometers on a trip from the Arabian Sea to London. Travel time was reduced to 10 days at 37 km/h or 8 days at 44 km/h [22]. The canal extends from the southern terminus of Port Tewfik of the city of Suez to the northern terminus of Port Said. More than 20,600 vessels traversed the canal (an average of 56 per day) in 2021 [23].

With passing locations in the Ballah Bypass Lake and the Great Bitter Lake [24] the original canal featured a single-lane waterway. The Suez Canal, according to Alois Negrelli’s design plans, contained no locks, with seawater flowing through it. The water in the canal north of the Bitter Lakes flows north in winter and south in summer. The current at Suez fluctuates with the tide [25].

Burchell [26] noted “*The canal was the property of the Egyptian government, but European shareholders, mostly British and French, owned the concessionary company which operated it until July 1956. On that date, President Gamal Abdel Nasser nationalized it—an event that led to the Suez Crisis of October–November 1956. The canal is operated and maintained by the state-owned Suez Canal Authority [27] (SCA) of Egypt. Under the Convention of Constantinople, it may be used ‘in time of war as in time of peace, by every vessel of commerce or of war, without distinction of flag’ [28]. Nevertheless, the canal has played an important military strategic role as a naval short-cut and choke point. Navies with coastlines and bases on both the Mediterranean Sea and the Red Sea (Egypt and Israel) have a particular interest in the Suez Canal. After Egypt closed the Suez Canal at the*

beginning of the Six-Day War on 5 June 1967, the canal remained closed for precisely eight years, reopening on 5 June 1975 [29].”

“The Egyptian government launched construction in 2014 to expand and widen the Ballah Bypass by 35 km to speed up the canal’s transit time. The expansion intended to nearly double the capacity of the Suez Canal, from 49 to 97 ships per day [30]. For LE 59.4 billion (US\$9 billion), this project was funded with interest-bearing investment certificates issued exclusively to Egyptian entities and individuals.”

“The Suez Canal Authority officially opened the new side channel in 2016. This side channel, at the northern side of the east extension of the Suez Canal, serves the East Terminal for berthing and unberthing vessels from the terminal. As the East Container Terminal is located on the Canal itself, before the construction of the new side channel it was not possible to berth or unberth” [26].

Ragab [31] determined *“Ships approaching the canal from the sea are expected to radio the harbor when they are within 28 km of the Fairway Buoy near Port Said. The canal did not need locks because of the flat terrain, and the minor sea level difference between each end is inconsequential for shipping. As the canal (Figure 10) has no sea surge gates, the ports at the ends would be subject to the sudden impact of tsunamis from the Mediterranean Sea and the Red Sea, according to a 2012 article in the Journal of Coastal Research [32].”*

“There is only one shipping lane with passing areas in Ballah-Bypass near El Qantara and the Great Bitter Lake (Figure 11). On a typical day, three convoys transit the canal, two southbound and one northbound. The passage takes between 11 and 16 hours at an average speed of around 8 knots (15 km/h). The low speed helps prevent erosion of the banks by ships’ wakes.”

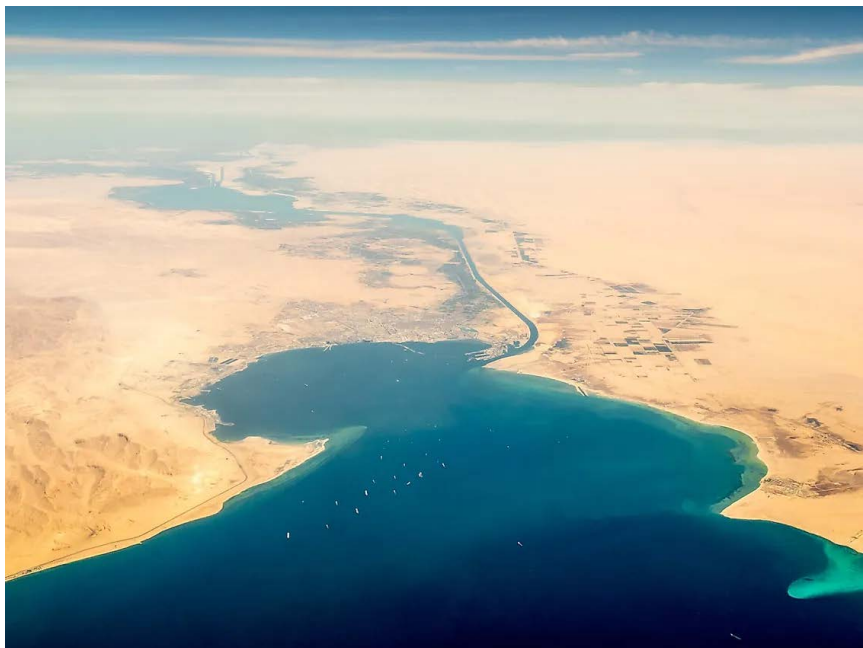


Figure 10. The Suez Canal [3].



Figure 11. Map of the Suez Canal [3].

“By 1955, about two-thirds of Europe’s oil passed through the canal. Around 8% of world sea trade is carried via the canal. In 2008, 21,415 vessels passed through the canal and the receipts totaled \$5.381 billion [33], with an average cost per ship of \$251,000” [31].

Curli [34] documented the “*New Rules of Navigation passed by the Suez Canal Authority (SCA) board of directors came into force on 1 January 2008 to organize vessels’ transit. The most important amendments include increasing the maximum breadth from 32 to 40 meters, allowing 19 m draft vessels to pass, and imposing a fine on vessels using non-SCA pilots inside the canal boundaries without permission. The amendments allow vessels loaded with dangerous cargo (such as radioactive or flammable materials) to pass if they conform with the latest amendments provided by international conventions. The SCA has the right to determine the number of tugs required to assist warships traversing the canal, to achieve the*

highest degree of safety during transit'.

Egyptian Maritime Data Bank [35] reported "In 1870 there were 486 transits which increased to 21,250 by 1966. The tonnage increased from 444,000 metric tons to about 278 million metric tons in 1966. In 2018 there were 18,000 transits, with 1139 million metric tons. Transit times in the 1870s were 40 hours but were reduced to 13 hours by 1939. Two-way traffic was not permitted in the original canal. However, after the creation of bays, two-way traffic was permitted. When a ship (Figure 12) enters the canal at either Port Said or Suez, ship tonnage is determined, passengers ride for free after 1950, and the ships are handled by one or two pilots when going through the Suez Canal. In August 2015, a new 35 km expansion channel, which ran parallel to the main channel, allowed two-way transit. The project was an attempt to boost Egypt's economy."



Figure 12. The USS Dwight D. Eisenhower, a nuclear-powered aircraft carrier, crossing the Mediterranean Seas on the way to Suez Canal [4].

"Most of the tonnage growth was a result of the Persian Gulf's increased shipment of crude oil and petroleum products. In 1913 the oil in the northbound traffic was 295,700 metric tons. By 1966 the tonnage increased to 168,700,000 metric tons. As a result of the Arab-Israel war, the canal was closed in 1967 and did not open until 1975. By then ships were going around the Cape of Good Hope and in 1977 a pipeline from Suez to Alexandria was opened. With the increased size of the tankers and other crude oil areas being developed the canal's importance in the international oil trade has declined."

"The passenger traffic peaked in 1945 at 984,000 because of aviation competition. Construction of the canal led to settlements in what had been, except for Suez, almost uninhabited arid territory. An additional 28,000 hectares were under

cultivation, and about 8 percent of the total population was engaged in agriculture, with approximately 10,000 commercial and industrial activities of various sizes. During the Suez Crisis in 1967, almost all the population was evacuated, and most of the settlements were severely damaged or destroyed during subsequent warfare. With the reopening of the canal in 1975, however, reconstruction of the area was begun, and most of the population had returned by 1978. Port Said was made a customs-free zone in 1975, and tax-free industrial zones have been established along the canal. The major urban centers are Port Said, with its east-bank counterpart, Al-Ismā'īlyyah, on the north shore of Lake Timsah; and Suez, with its west-bank outpost, Būr Tawfīq. The Nile via the Al-Ismā'īlyyah Canal supplied water for irrigation, domestic, and industrial use.”

“In 1980 the Ahmad Hamdi Road tunnel was opened, connecting Egypt proper with its governorate of Shamāl Sīnā. About 1.6 km of the tunnel passes beneath the canal itself. In 2014, the Egyptian government built additional tunnels that ran below the canal, which were opened in May 2019. The expansion project also includes the development of additional transportation infrastructure in the surrounding area, aims to reclaim some 1.6 million hectares of land for cultivation, and plans to develop a sprawling free-trade zone along the canal.”

“Before August 2015, the canal was too narrow for uncontrolled two-way traffic, so ships had to pass in convoys and use bypasses. The bypasses were 78 km out of 193 km (40%). From north to south, the entrances are the Port Said Bypass 36.5 km, the Ballah Bypass and Anchorage 9 km, Timsah Bypass 5 km, and the Deversoir Bypass (northern end of the Great Bitter Lake) 27.5 kilometers. The bypasses were completed in 1980. Typically, it would take a ship 12 to 16 hours to transit the canal. The canal's 24-hour capacity was about 76 standard ships” [35].

Saleh and Wasmine [36] found “In August 2014, Egypt chose a consortium that includes the Egyptian army and global engineering firm Dar Al-Handasah to develop an international industrial and logistics hub in the Suez Canal area. The consortium began the construction of a new canal section from 60 to 95 km combined with expansion and deep digging of the other 37 km of the canal [37]. This allowed navigation in both directions simultaneously in the 72-kilometer-long central section of the canal. These extensions [30] [38] [39] were formally opened on 6 August 2015 by President Al-Sisi”.

Fletcher [40] suggested “Since the canal does not cater to unregulated two-way traffic, all ships transit in convoys on a regularly scheduled 24-hour basis. Each day, a single northbound convoy starts at 04:00 A.M. from Suez. At dual-lane sections, the convoy uses the eastern route [40]-[42]. Synchronized with this convoy's passage is the southbound convoy. It starts at 03:30 A.M. from Port Said and so passes the Northbound convoy in the two-lane section. A railway on the west bank runs parallel to the canal for its entire length.”

“The five pontoon bridges were opened between 2016 and 2019 [43]. They are designed to be movable and can be completely rotated against the banks of the canal to allow shipping through, or individual sections can be moved to create a

narrower channel. Six new tunnels for cars and trains are also planned across the canal [3] [44]. The Ahmed Hamdi is the only tunnel connecting Suez to the Sinai [40].

3.2. Economic Impact of the Suez Canal

Pelletier [45] determined “*Economically, after its completion, the Suez Canal benefited primarily the sea trading powers of the Mediterranean countries, which now had much faster connections to the Near and Far East than the North and West European sea trading nations such as Great Britain or Germany [46]. The main Habsburg trading port of Trieste with its direct connections to Central Europe experienced a meteoric rise at that time [47] [48].*”

“The time saved in the 19th century for an assumed steamship trip to Bombay from Brindisi and Trieste was 37 days, from Genoa 32, from Marseille 31, from Bordeaux, Liverpool, London, Amsterdam, and Hamburg 24 days. At that time, it was also necessary to consider whether the goods to be transported could bear the costly canal tariff. This led to a rapid growth of Mediterranean ports with their land routes to Central and Eastern Europe. According to today’s information from the shipping companies, the route from Singapore to Rotterdam through the Suez Canal will be shortened by 6000 kilometers and thus by nine days compared to the route around Africa. As a result, liner services between Asia and Europe save 44 percent CO₂ (carbon dioxide) thanks to this shorter route. The Suez Canal has a correspondingly important role in the connection between East Africa and the Mediterranean region [49]-[51].”

“In the 20th century, trade through the Suez Canal came to a standstill several times, due to the two world wars and the Suez Canal crisis. Many trade flows were also shifted away from the Mediterranean ports towards Northern European terminals, such as Hamburg and Rotterdam. Only after the end of the Cold War, the growth in European economic integration, the consideration of CO₂ emission, and the Chinese Silk Road Initiative are Mediterranean ports such as Piraeus and Trieste again at the focus of growth and investment [49] [52]-[55]. The Suez Canal set a new record [56] with annual revenue of \$9.4 billion in USD for the fiscal year that ended 30 June 2023” [45].

The Ministry of Investment [57] identified “*The Suez Canal Economic Zone, sometimes shortened to SCZONE, describes the set of locations neighboring the canal where customs rates have been reduced to zero to attract investment. The 461 km² zone is within the governorates of Port Said, Ismailia, and Suez. Projects in the zone are collectively described as the Suez Canal Area Development Project (SCADP) [57] [58]. The plan focuses on the development of East Port Said and the port of Ain Sokhna, and hopes to extend to four more ports at West Port Said, El-Adabiya, Arish, and El Tor [59]. The zone incorporates the four “Qualifying Industrial Zones” at Port Said, Ismailia, and Suez, a 1996 American initiative to encourage economic ties between Israel [60] and its neighbors”.*

3.3. Environmental Impact of the Suez Canal

Bitter Lakes became the largest inland water bodies through which the Suez Canal was built, providing 85% of the Canal's water volume and over 24% of its length⁶. Inclusion of these previously small and hyper-saline (up to 160 g/L) lakes into the Canal increased their size and water mass along with decreasing salinity to 41 - 45 g/L. Being affected mainly by shipping along with the urban and recreational development of the western shore, the Bitter Lakes remain their environmental importance for wintering and migratory waterfowl and therefore internationally recognized as the same-name Important Bird & Biodiversity Area. The initial Bitter Lakes' function as a barrier to marine biota from the Red Sea to the Mediterranean gradually weakened as thermohaline conditions equalized along the entire Canal (whereby various engineering solutions to counteract invasions were considered in the context of the Canal's expansion).

The Lake Timsah is another unique inland water body included into the Suez waterway which also receives freshwater from Nile through Ismailia Canal built for water supply purposes at the same time as the Suez Canal. Unlike the oligotrophic Bitter Lakes, Timsah is eutrophic, stratified both in the water column and laterally in salinity (20 to 40 g/L)⁷. More intensive contamination of Timsah is fueled by Ismailia Canal which collects agricultural drainage, as well as insufficiently treated domestic and industrial wastewater from the vast territory drained by it⁸.

As can be seen, the Suez Canal at the time of construction of which ecological consequences were not considered has linked into a single hydrobiological system several water bodies quite different in genesis and baseline ecological functions and facilitated their environmental stress now reflected in their current protection status.

The environmentally significant impacts of the Suez Canal which became apparent only many decades after its opening can be roughly divided into direct, caused by the artificial water body itself connecting the Mediterranean Sea with the Red Sea, and indirect, arising from the subsequent development of the area adjacent to the Canal, as well as the sustainable redistribution of global shipping with a higher load on the seascapes linked by the Canal.

The Canal's water mass produces a very strong environmental gradient which not all organisms can successfully overcome. The natural seascapes connected by the Suez Canal are also not equal in terms of both vulnerability to invasions and the presence of species with invasive potential [61]-[63]: Erythraean species—algae,

⁶El-Serehy H.A., *et al.* Aquatic ecosystem health and trophic status classification of the Bitter Lakes along the main connecting link between the Red Sea and the Mediterranean//Saudi Journal of Biological Sciences. 2018. Vol. 25. P. 204-212.

⁷El-Serehy H.A., *et al.* Assessing water quality and classifying trophic status for scientifically based managing the water resources of the Lake Timsah, the lake with salinity stratification along the Suez Canal//Saudi Journal of Biological Sciences. 2018. Vol. 25. P. 1247-1256.

⁸Geriesh M.H., *et al.* Problems of drinking water treatment along Ismailia Canal Province, Egypt//Journal of Zhejiang University. Science B. 2008. Vol. 9. No. 3. P. 232-242.

invertebrates, and fish (also known altogether as Lessepsian bioinvaders)—were found much better positioned to colonize the eastern Mediterranean in this human-transformed environment, displacing native species, disrupting food chains in marine ecosystems, and reducing the quality of the affected ecosystem services⁹.

In relation not only to The Nile Delta Fan, but also to the entire Eastern Mediterranean Sea, it is possible to speak about the overlapping ecological impacts of the Suez Canal and another major hydraulic project—the regulation of the Nile River flow that significantly reduced the volume of freshwater discharge into the Mediterranean Sea and thus contributed to the more successful spread of Lessepsian bio invaders.

One of the physical factors contributing to the predominantly unidirectional invasive flow is the water circulation: the main water flow in the Canal is northward, and it entrains all categories of passively swimming organisms, facilitating their penetration from the Red Sea to the Mediterranean. Against this background, the migration of several ecologically adaptive species of active-swimming organisms (like adult fishes) together with associated parasites is also confirmed to be predominantly northward¹⁰. Invasions in the opposite direction, i.e. from the Mediterranean basin to the Red Sea, also occur, but are smaller in spatial extent and represented by a relatively small number of species¹¹.

By its outcomes, Lessepsian invasion is estimated to be largely irreversible, and it is far from being limited to the waters immediately adjacent to the Suez Canal, gradually encompassing the entire Mediterranean basin. Current discussions around Canal's invasive role are accompanied by expanding interpretations of the invaders' genome as one of the prerequisites for their successful acclimatization¹².

Periodically published data on the “exoneration” of one or another species considered invasive, the spread or genetic diversity of which is reasonably assumed to be independent of the Canal¹³, do not change the general picture: having become one of the most striking examples of bio invasions for the global environmental community, now effectively regulated to a greater or lesser extent in various parts of the world, the Suez Canal itself continues to retain the function of a powerful and poorly regulated invasive corridor the negative impact of which is not compensated—only as a prospect are considered the increase of efficiency of the Canal's salinity barrier (due to discharge of brines from desalination plants to Bitter

⁹Galil, B.S. A Sea, a Canal, a Disaster: The Suez Canal and the Transformation of the Mediterranean Biota//C. Lutmar and Z. Rubinovitz (eds.), *The Suez Canal: Past Lessons and Future Challenges*, Palgrave Studies in Maritime Politics and Security. 2023. P. 199-215.

¹⁰Diamant, A. Red-Med Immigration: A Fish Parasitology Perspective, with Special Reference to the Myxosporea//D. Golani and B. Appelbaum-Golani (Eds.). *Fish Invasions of the Mediterranean Sea: Change and Renewal*. 2010. P. 85-97.

¹¹Malaquias, M.A.E., *et al.* The Suez Canal as a Revolving Door for Marine Species...//Aquatic Invasions. 2017. Vol. 12, Issue 1. P. 1-4.

¹²Azzurro, E. *et al.* Right out of the Gate: The Genomics of Lessepsian Invaders in the Vicinity of the Suez Canal//Biological Invasions. 2022. Vol. 24. P. 1117-1130.

¹³Bos, A.R., Ogwang, J., Bariche, M. *et al.* Anti-Lessepsian Migration Rectified: The Comber *Serranus Cabrilla* (L. 1758) Existed in the Red Sea Prior to the Suez Canal Opening//Marine Biology. 2020. Vol. 167. Art. No. 126.

Lakes), as well as, probably, the construction of locks [64].

Against the background of these issues, such problems as the discharge of a variety of contaminants from the Canal in dissolved and suspended forms and those indirect ecologically significant impacts of the Canal the counteraction to which is not even considered on the international agenda are overshadowed. More specifically, the geography of acoustic impact of shipping on the marine environment is far from being limited to the Canal and the seas it connects and extends along all the navigation routes intensified by the Canal.

For the Canal itself, the ecological effects of navigation have been studied in relative detail showing seasonal and inter-annual dynamics, association with types of vessels, prevailing navigation directions and other factors. In particular, the Suez Canal's feature as a mediator of shipping-based bio invasions is a relatively small share of ballast-weighted ships and the predominant importance of hull-mediated invasions provoked by cruise ships with their relatively high surface area susceptible to fouling¹⁴.

The spreading of ship-borne invasions is more extensive than that of water-borne ones as they are linked not only to anchorages but also to remote ports of loading/unloading and servicing of vessels. The absence of the Canal, of course, would not exclude this factor of the transformation of marine habitats of the seas it connects, simply redistributing the impacts of shipping to other water areas. The recent expansion of the Canal has further increased the invasive effect of the associated shipping, virtually the only obstacle to which is seen as the prospective tightening of international maritime legislation and international standards for ship maintenance (the periodic cleaning of their hulls from fouling).

The Port of NEOM, the largest marine terminal under construction, which is a component of much larger and more ambitious development project of the same name in the Kingdom of Saudi Arabia, is likely to be a closest example of application of the current best practices and environmental standards developed with the negative experience of the Suez Canal considered. Ideally, all major projects whose transportation scheme involves the use of the Suez Canal should consider its environmental impacts and, where possible, compensate for them.

In March of 2021 an extraordinary March heat wave preceded the cold front and sandstorm that contributed to the canal-blocking incident (**Figure 3**). According to Maximiliano Herrera [65] *“the previous day previously, Kharga, Egypt, recorded a scorching temperature of 44 degrees Celsius (111.2 °F), just 0.2 degrees Celsius below the highest March temperature ever recorded in the nation. The day of the sandstorm (March 23), Luxor, Egypt, hit 43.6 degrees Celsius—just 0.6 degrees Celsius below the March national record. On the day after the sandstorm, Mitribah, Kuwait hit 44.6 degrees Celsius (112.3 °F)—the hottest temperature ever recorded in the Arabian Peninsula in March”*. Eli Bou-Zeid found *“The simulations showed that what was very unique about this storm is that, first, it was*

¹⁴Bereza, D., D. Rosen, and N. Shenkar Current trends in ship movement via the Suez Canal in relation to future legislation and mitigation of marine species introductions//Management of Biological Invasions (2020) Volume 11, Issue 3: 476-492.

preceded by a very hot period, so the land that was not covered with vegetation would be drier and it would be easier to extract sand grains by saltation and creep from surface.”

“Extreme heat dries the soil, allowing winds to more readily mobilize clay, silt, sand grains and create a dust storm. Unusually hot and dry conditions preceding an event can be responsible for its near-record intensity. Climate change maybe increasing the incidence of such extreme heat events and reduced visibility may have played a role in the ship’s blockage of the Suez Canal. Wind appears to be the main culprit for the grounding of the ship, however, with the sandstorm’s strong and variable winds did make it more difficult to navigate the passage. When the strong cold front swept through Egypt on March 23, 2021, the winds behind the front were able to loft an unusual amount of dust (clay and silt) and sand into the air because of the earlier hot conditions. That created difficult circumstances for navigation on the Suez Canal” [65].

Richard Cameron [66] said: *“Depending on their cargo volume and location, sea-ports can have an impact on the air quality and therefore on the health of the community. At a port, the transportation industry has made it a top priority to reduce all our environmental impacts, and to track our progress in doing so. As diverse as these issues are, some port activities can have a massive impact on the local area. A case in point, the dredging at a port can be a threat to local water quality. Emissions in ports, particularly those emitted from ships, such as carbon dioxide, mono-nitrogen oxides and other harmful chemicals, are among the toxic elements to increase fourfold by 2050, with no sign of a slowdown, as ships are said to be no more efficient than they were around two decades ago. So what solutions are available for ports in tackling this vast array of environmental impacts?”*

“This year we are marking the tenth anniversary of the Green Port Policy, which is the Port of Long Beach commitment becoming a leader in environmental stewardship. The port has backed that commitment with an investment estimated at more than \$500 million, our industry partners have spent even more, and the results have been clear. We’ve seen an 82% reduction in diesel particulate exhaust from port-related sources in the last 10 years. Because of our ‘Clean Trucks Program’, we have 14,000 drayage trucks at work in the port that are from the year 2007 or newer. There are 78 acres of kelp beds in port waters. And it doesn’t end there. We are working on an update to our ‘Clean Air Action Plan’, and we are aiming to become a zero-emissions port [66].”

Abd-Elhamid *et al.* [67] suggested *“Climate change and human activities may yield serious implications for coastal areas. Rising sea levels provide specific challenges that might significantly affect coastal areas, risking their ecosystems, construction projects and livelihoods. Sea levels increased by 10 and 20 cm in the 20th century, and the IPCC predicts a rise of 20 and 88 cm by the last decade of the 21st century. This rise might have broad consequences for coastal areas, including shoreline erosion and submergence of coastal communities. Additionally, anthropogenic activities like land use changes could expand such things. This study seeks*

to evaluate the impacts of climate change and anthropogenic activities in the coastal area of Port Said city, Egypt. Significant alterations in land use have been observed in this area during the past few decades, alongside the impact of increasing sea levels. Geographic Information Systems (GIS), Remote Sensing data and numerical models are employed for achieving the above objectives. GIS and remote sensing utilized satellite imagery to monitor the land use changes (LUC) during the previous 50 years (1973-2023). Moreover, GIS with Digital Shoreline Analysis System (DSAS) are employed to monitor the shoreline change (SLC) utilizing satellite imagery from the previous 50 years and to forecast future alterations over the next 10 and 20 years.”

“The results demonstrate significant changes in the land cover due to anthropogenic activities where urbanization has increased 10 times, agricultural land has increased 16 times, on the contrast, the bare land decreased 48%. The coastline position has shifted, exhibiting varying values around the beaches over the previous 50 years, and it is anticipated to continue increasing in the next 10 - 20 years. Between 1973 and 2023, the erosion rate (EPR) fluctuated from 5.66 to 12.8 m/year, while the Net Shoreline Movement (NSM) varied from 209 to 640.2 m. The results showed significant changes in the shoreline and land cover at Port Said due to climate change and anthropogenic activities that necessitate the implementation of adequate protective measures. The findings of this study may assist policymakers in formulating adaptation plans to protect this crucial area from climate change and human activities” [67].

1) Al Adabeya Port storage facility in Egypt was built in 1975 and dedicated for the storage of dry bulk [68]. It is situated about 125 km east of Cairo easily reachable by good condition highway, The nearest larger city is Suez city in Suez governorate (17 km to the North). The storage is an open yard (**Figure 13**) designed for temporary storage of shipped goods. The yard has two gates, one of them (at the NE corner of the yard) is the emergency gate. It is estimated that about 220 tons of obsolete lindane have been stored at the Al Adabeya Port since 1998. These obsolete stockpiles are packed in 25 kg heavy paper bags supported by a plastic outer wrapping and stored in 3 by 6 m standard containers occupying an area of 5850 m² (225 × 26 m). The soil in the yard has not been sampled to establish the effect on the soil quality especially the content of chlorinated pesticides. The levels of exposures of the stored pesticides are unknown. There are records of the levels of radioactivity direct where pesticide containers are stored.

2) Detailed inventory is needed and therefore all the containers must be inspected. Meanwhile, the Chemical Weapons Sector has analyzed the contents of the containers through its accredited laboratories. It is understood that the obsolete and POPs pesticides may be stored in a substandard way and limit. There may be the possibility of emissions because of high ambient temperatures; however, there are no environmental records. The proposed project involves the handling, packaging, transporting and disposal of these hazardous stockpiled pesticides, as

well as the remediation of any site contamination, if required. Consequently, the Environmental and Social Impact Assessment (ESIA) was prepared for the implementation of the National Implementation Plan in the country. The major aim of ESIA is to put in place a decision-making tool for environmentally sound management of obsolete lindane stockpile in Al Adabiya Port, Suez.



Figure 13. Al-Adabiya Port, Suez, Egypt. Storage of liquid and dry chemicals. Photo Credit: EEAA.

4. Summary

The primary objective of this study was to document the historical, economical, and environmental impacts of connecting the Mediterranean Sea and the Red Sea via a canal. After the completion of the Suez Canal in 1869 the canal became an economically lifeline for Egypt. However, the economic gains were partially offset by negative environmental impacts. The canal's opening created the first salt-water passage between the Mediterranean Sea and the Red Sea. By shortening the travel time, ship carbon emissions were reduced. The impact of port activities on the environment depends on their cargo volume and location, seaports can have an impact on the air quality and therefore on the health of the community. Climate change and human activities may yield serious implications for coastal areas. Rising sea levels provide specific challenges that might significantly affect coastal areas, risking their ecosystems, construction projects and livelihoods.

The chemical storage at ports along the Suez Canal on the Red Sea and the Mediterranean Sea are a risk to the groundwater, the surface water, and air quality. The salinity barrier to migration was removed, with the creation of the Suez Canal, and animals and plants from the Red Sea have begun colonizing the eastern Mediterranean. Since the 1880s, exotic species from the Indo-Pacific Ocean have become a significant component of the Mediterranean ecosystem and were introduced into the Mediterranean via the canal. They are already endangering some local and endemic species and impacting their ecology. The results showed significant changes in the shoreline and land cover due to climate change and

anthropogenic activities that necessitate the implementation of adequate protective measures. The findings of this study may assist policymakers in formulating adaptation plans to protect this crucial area from climate change and human activities.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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