

# Natural and Anthropogenic Environmental Risks to the Rhine River and Delta

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## Abstract

The Rhine River in Western Europe flows from two small headwaters in the Alps of east-central Switzerland and drains north and west through Netherlands to the North Sea. It has been an international waterway since the Treaty of Vienna in 1815. Approximately, 870 km of the Rhine River is navigable as far as Rheinfelden on the Swiss-German border. Its catchment area, including the delta area, exceeds 220,000 km<sup>2</sup>. The Rhine River is a classic example of a political and cultural boundary line and as an artery of cultural and political unification. The primary objective of this paper is to document the natural and anthropic risks to the Rhine River and Delta including navigation, stream capture, settlement, invasions, and trade. Environmental risks include contamination, pollution, industrial and urban wastewater, overfishing, threats to food supply, urban development, channelization, dams, shoreline erosion, and flooding.

## Keywords

Rhine, Microplastics, Contamination, Pollution, Stream Capture, WWI, WWII, Sedimentation, Rhine Delta

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## 1. Introduction

The Rhine River in Western Europe is among the most important arteries of industrial transport in the world and culturally and historically one of the great rivers of the continent. Since the Roman Empire, the Rhine River has been one of Europe's leading transport routes. One-fifth of the world's chemical industries are now manufacturing along the Rhine. The Rhine River flows into Netherlands and

becomes a delta. Amsterdam, with its many canals, is located on the Rhine Delta. The Rhine River was important as a waterway in the Holy Roman Empire and is supported by the many fortifications and castles built along it. The long-term goal of French foreign policy, since the Middle Ages, was establishing “natural borders” with Germany on the Rhine. The language border was originally much farther to the west. In the modern era, it has become a symbol of German nationalism. The primary objective of this paper is to document the natural and anthropic risks to the Rhine River and Delta including navigation, stream capture, settlement, invasions, and trade. Environmental risks include pollution, contamination, industrial and urban wastewater, overfishing, threats to food supply, urban development, channelization, dams, shoreline erosion, and flooding.

## 2. Study Site

### 2.1. Natural Resources

At the beginning of the Holocene (~11,700 years ago), the Rhine occupied its Late-Glacial valley (**Figure 1**) and (**Figure 2**). As a meandering river, it reworked its ice-age floodplain. As sea-level rise continued in Netherlands, the formation of the Holocene Rhine-Meuse<sup>1</sup> delta began (~8000 years ago) [1]-[4]. Coeval absolute sea-level rise and tectonic subsidence have strongly influenced delta evolution. Other factors of importance to the shape of the delta are the local tectonic activities of the Peel Boundary Fault, the substrate and geomorphology, as inherited from the Last Glacial and the coastal-marine dynamics, such as barrier and tidal inlet formations.

Since ~3000 yr BP (=years Before Present), human impact is seen in the delta. As a result of increasing land clearance (Bronze Age agriculture), in the upland areas (central Germany) [5], the sediment load of the Rhine has strongly increased, and delta growth has speeded up. This has caused increased flooding and sedimentation, ending peat formation in the delta. In the geologically recent past, the main process of distributing sediment across the delta has been shifting river channels to new locations on the floodplain (termed avulsion). Over the past 6000 years, approximately 80 avulsions have occurred. Direct human impact in the delta began with the mining of peat for salt and fuel from Roman times onward [5]. This was followed by embankment of the major distributaries and damming of minor distributaries, which took place in the 11<sup>th</sup> - 13<sup>th</sup> century AD. Thereafter, canals were dug, bends were straightened and groynes were built to prevent the river’s channels from migrating or silting up.

The discharge of the Rhine is divided into three branches: the Waal (6/9 of total discharge), the Nederrijn-Lek (2/9 of total discharge), and the IJssel (1/9 of total discharge). This discharge distribution has been maintained since 1709 by river engineering works including the digging of the Pannerdens canal and the installation, in the 20th century, of a series of weirs on the Nederrijn.

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<sup>1</sup>Also Maas, Meuse.

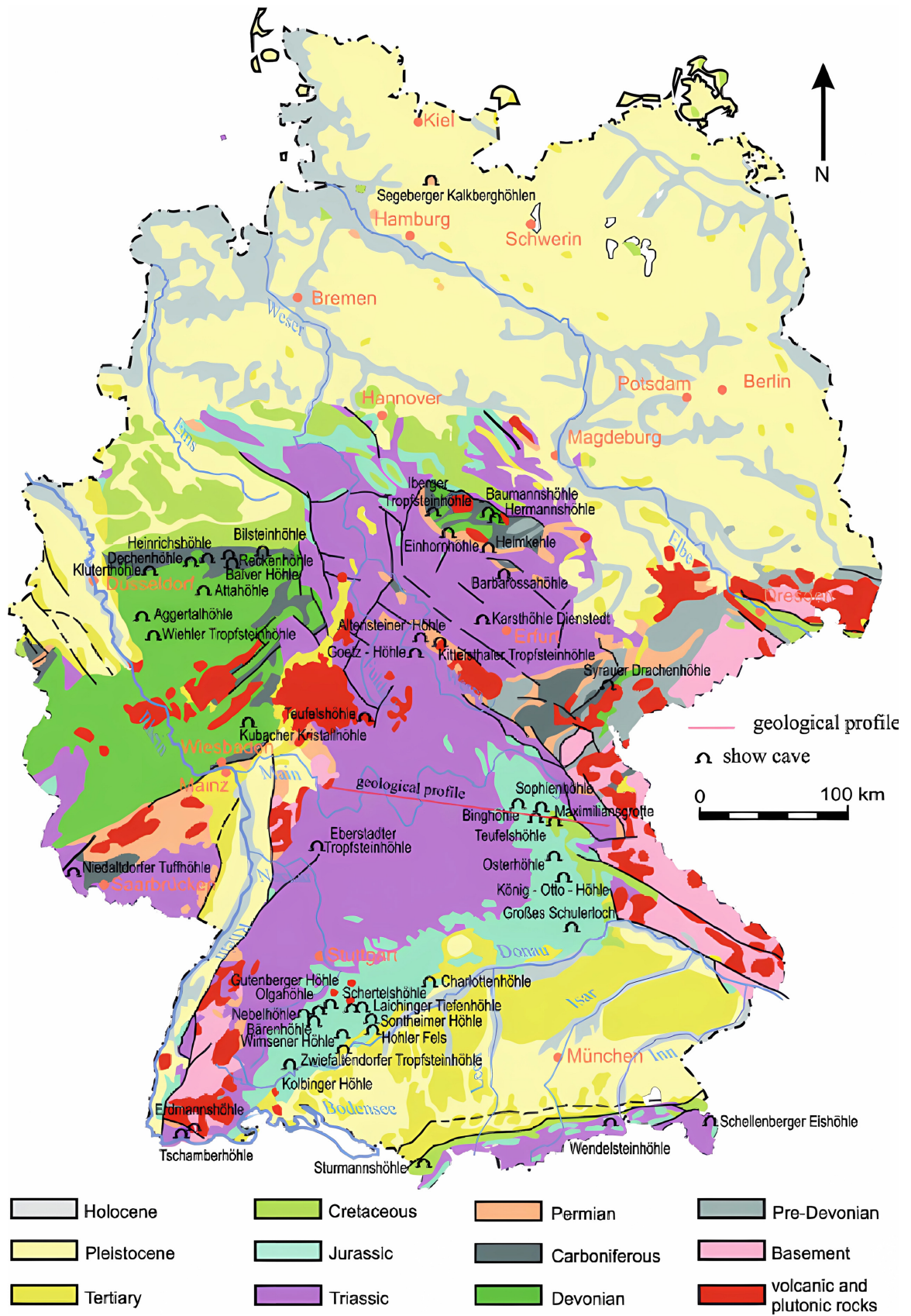
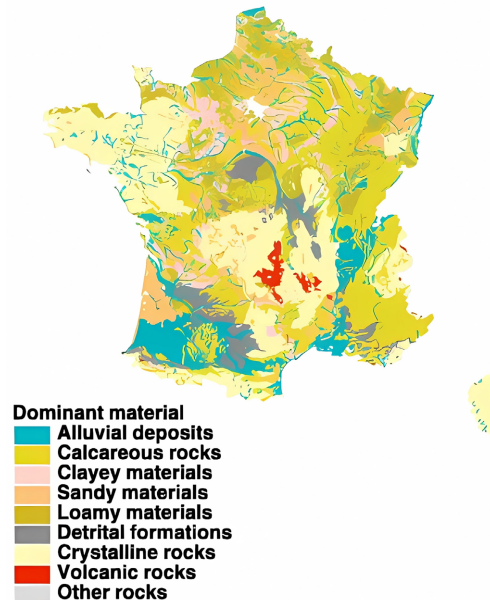


Figure 1. The geology map of Germany. Photo Credit: numis.niedersachsen.de.

### Detail of the Soil Geographical Data Base of France (INRA Orléans)



**Figure 2.** The geology map of France. Photo Credit: proceedings.esri.com.

## 2.2. Stream Capture

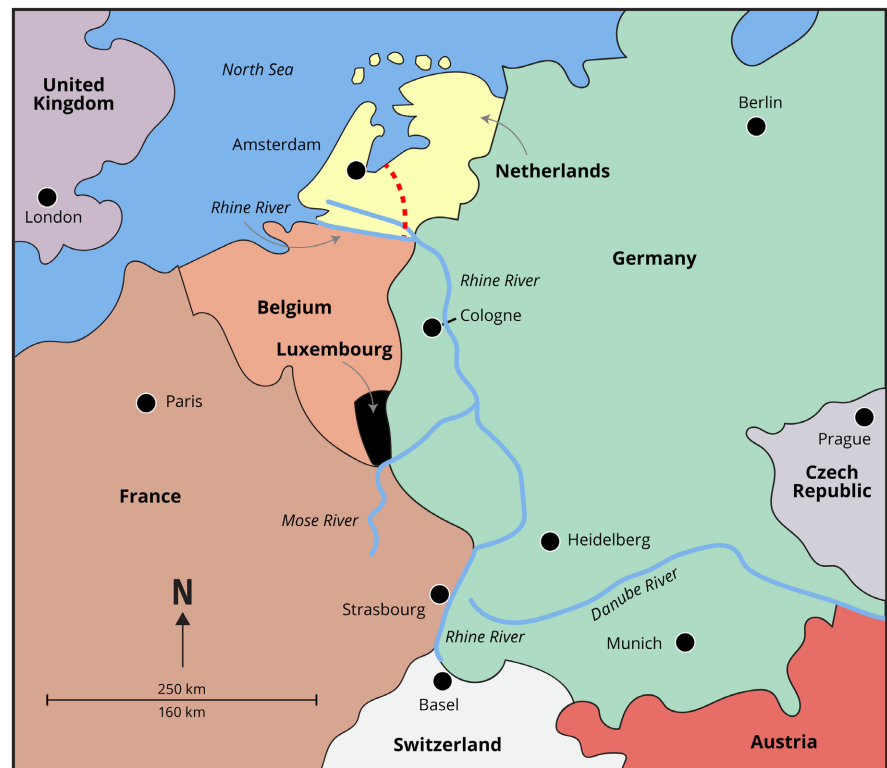
The watershed of the Rhine reaches into the Alps today, but it did not start out that way. In the Miocene period, the watershed of the Rhine reached south, only to the Eifel and Westerwald hills, about 450 km north of the Alps. The Rhine then had the Sieg as a tributary, but not yet the Moselle River. The northern Alps were then drained by the Danube. The “total length of the Rhine”, to the inclusion of Lake Constance<sup>2</sup> and the Alpine Rhine is more difficult to measure objectively. It was cited as 1232 km by the Dutch Rijkswaterstaat in 2010.

Through stream capture of the Danube River near Strasbourg (**Figure 3**), the Rhine extended its watershed southward [6] [7]. By the Pliocene period, the Rhine had captured streams down to the Vosges Mountains. The northern Alps were then drained by the Rhine. By the early Pleistocene period, the Rhine had captured most of its current Alpine watershed from the Danube (**Figure 4**). Since that time, the Rhine has added the watershed above Lake Constance.

## 2.3. Geology of the Rhine Valley

Around 2.5 million years ago (ending 11,600 years ago) was the geological period of the Ice Ages. Since approximately 600,000 years ago, six major Ice Ages have occurred, in which sea level dropped 120 m and much of the continental margins became exposed. In the Early Pleistocene, the Rhine followed a course to the northwest, through the present North Sea. During the so-called Anglian glaciation

<sup>2</sup>Also Bodensee.



#### Legend

	Switzerland		Belgium		Luxembourg
	Czech Republic		France		Water
	Austria		Germany		Canal
	United Kingdom		Netherlands		Rivers

**Figure 3.** The stream capture of the Danube River by the Rhine River. Map by Cruz Dragosavac.

(~450,000 yr BP), the northern part of the present North Sea was blocked by the ice and a large lake developed, that overflowed through the English Channel. This caused the Rhine's course to be diverted through the English Channel. During interglacial periods, when sea level rose to approximately the present level, the Rhine built deltas, in what is now Netherlands.

The last glacial ran from ~74,000 (BP), until the end of the Pleistocene (~11,600 BP) [3]. In northwest Europe, it saw two very cold phases, peaking around 70,000 BP and around 29,000 - 24,000 BP. The last phase slightly predates the global last ice age maximum. During this time, the lower Rhine flowed roughly west through Netherlands and extended to the southwest, through the English Channel, and finally, to the Atlantic Ocean. The English Channel, the Irish Channel, and most of the North Sea were dry land, mainly because sea level was approximately 120 m lower than today.

Most of the Rhine's current course was not under the ice during the last Ice

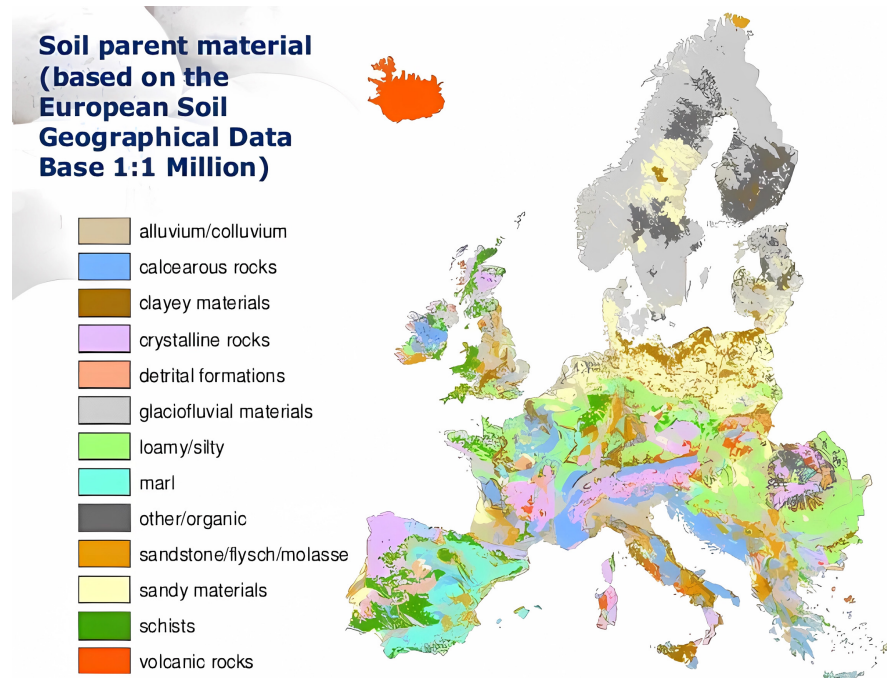


**Figure 4.** The Rhine River flows through Netherlands, Belgium, Germany, France, and Switzerland. The Rhine River shortened the Danube by stream capture which affected the entire Danube watershed and the water flow in the Danube. Map by Cruz Dragosavac.

Age; although, its source was still a glacier. A tundra, with Ice Age flora and fauna, stretched across middle Europe, from Asia to the Atlantic Ocean. Such was the case during the last glacial maximum, ca. 22,000 - 14,000 yr. BP, when ice sheets covered Scandinavia, the Baltics, Scotland, and the Alps, but left the space between as open tundra. Loess (wind-blown silt) arose from the South and North Sea plain settling on the slopes of the Alps, Urals, and the Rhine Valley, rendering the valleys facing the prevailing winds especially fertile.

Most of Rhine Valley (**Figure 5**) has temperate brown and deep brown soils [8]. Their formation is dependent on hydrologic conditions, vegetation, relief, and human intervention (**Figure 6**). The Rhine Valley's most productive soils are developed in alluvial and loess deposits on the floodplain, adjacent terraces, and stream banks. They range from black to extremely fertile brown soil types, and most of them are arable land under cultivation. The finest soils include those in river valley

between Mainz, Germany to Basel, Switzerland. Loess covered stream banks and uplands are used for agriculture, viticulture, and grazing. With increasing elevation, soils are suitable only for grazing or forestation. Along The North Sea littoral in the northwest there are some extensive areas of sand, marsh, and mudflats (**Figure 7**) that are covered with rich soil suitable for grazing and growing crops.



**Figure 5.** Magnificent Gothic Dom (cathedral) in Colone. Photo Credit: eea.europa.edu.

#### 2.4. End of the Last Ice Age

As northwest Europe slowly began to warm up from 22,000 years ago onward, frozen subsoil and expanded alpine glaciers began to thaw, and fall-winter snow covers melted in spring. Much of the discharge was routed to the Rhine and its downstream extension [2]-[4]. Rapid warming and changes of vegetation, to open forests, began about 13,000 BP. By 9000 BP, Europe was fully forested. With globally shrinking ice cover, ocean water levels rose and the English Channel and North Sea re-inundated. Meltwater, adding to the ocean and land subsidence, drowned the former coasts of Europe.

About 11,000 years ago, the Rhine estuary was in the Strait of Dover. There remained some dry land in the southern North Sea connecting mainland Europe to Britain. About 9000 years ago, that last divide was overtopped/dissected. Man was already resident in the area when these events happened. In the last 7500 years the situation of tides, currents and landforms has resembled the present. Rates of sea level rise dropped such that natural sedimentation [3] [4] by the Rhine and coastal processes widely compensate for transgression by the sea. In the southern North Sea, due to ongoing tectonic subsidence, the coastline and seabed are sinking at the rate of about 1 - 3 cm (0.39 - 1.18 in) per century (1 m



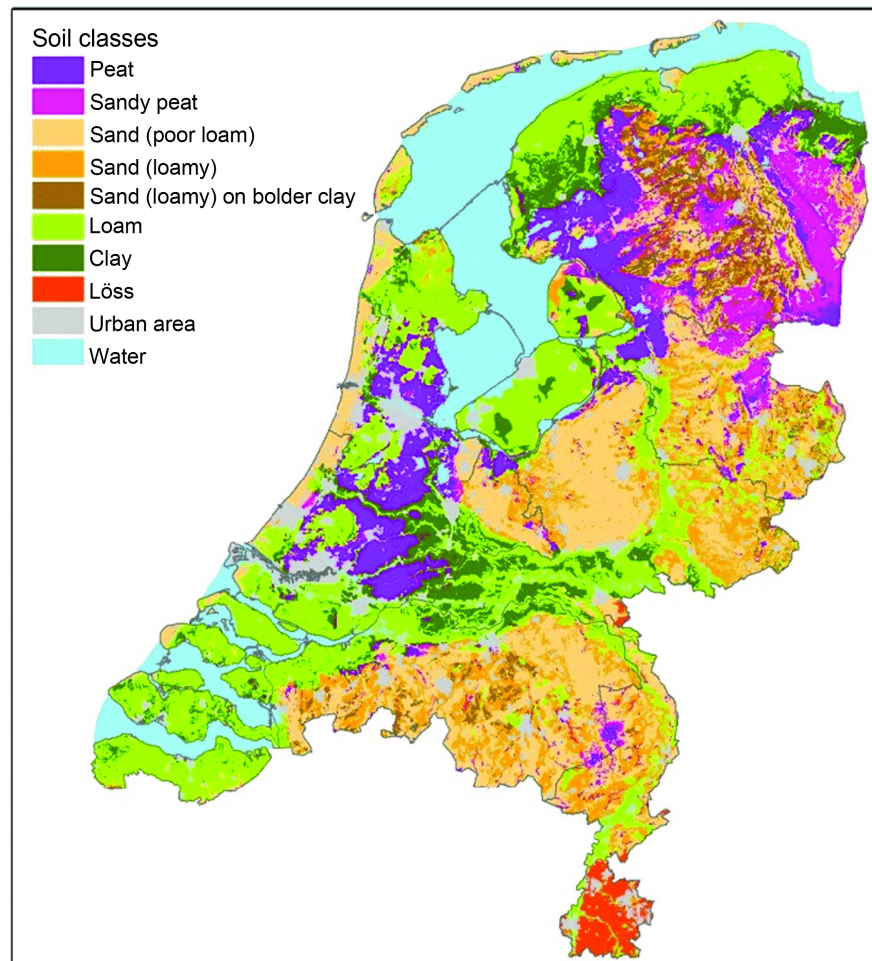
**Figure 6.** Soils map of the Rhine River valley. Photo Credit: Phinterest.fr.

in the last 3000 years).

About 7000-5000 BP, a general warming encouraged migration of all former ice-locked areas, including up the Danube and down the Rhine by peoples from the east. A sudden massive expansion of the Black Sea occurred as the Mediterranean Sea burst into it at about 7500 BP.

## 2.5. Holocene Rhine Delta Formation

At the land-ocean interface, large river deltas are major sinks of sediments and associated matter [9]. During the previous centuries, many studies have been conducted on the formation of the Rhine Delta and over bank deposits on the Rhine floodplains. This paper is an attempt to summarize these research results



**Figure 7.** Soils map of Netherlands and the Rhine River Delta. Photo Credit: Aadrik Tiktak, ResearchGate.

with emphasis on the amounts and changes of overbank fines trapped in the Rhine Delta. Materials and methods of sediment trapping in the Rhine Delta throughout the Holocene were quantified using a detailed database of the Holocene delta architecture. Additional historical data allowed the reconstruction of the development of the river's floodplain during the period of direct human occupation and modification of the river. Using heavy metals as tracers, overbank deposition rates over the past century were determined. Measurements of overbank deposition and channel bed sediment transport in recent years, together with modelling studies of sediment transport and deposition, have provided a detailed insight into the present-day sediment deposition on the floodplains. Estimated annual suspended sediment deposition rates were about  $1.4 \times 10^9 \text{ kg year}^{-1}$  between 6000- and 3000 years BP and increased to about  $2.1 \times 10^9 \text{ kg year}^{-1}$  between 3000- and 1000-years BP [9]. After the rivers were embanked by artificial levees between 1100 and 1300 AD, the amount of sediment trapped in the floodplains was reduced to about  $1.16 \times 10^9 \text{ kg year}^{-1}$ .

However, when accounting for reattainment of previously deposited sediment,

the actual sediment trapping of the embanked floodplains was about  $1.86 \times 10^9$  kg year<sup>-1</sup>. Downstream of the lower Waal branch an inland delta developed that trapped another  $0.4 \times 10^9$  kg year<sup>-1</sup> of overbank fines. Since the width of channel was artificially reduced and the banks were fixed by a regular array of groynes around 1850, the average rates of deposition on the embanked floodplains have been  $1.15 \times 10^9$  kg year<sup>-1</sup>. Scenario studies show that the future sediment trapping in the lower Rhine floodplains might double. The variations in amounts of sediment trapped in the Rhine delta during the past 6000 years are largely attributed to changes in land use in the upstream basin. At present, the sediment trapping efficiency of the floodplains is low and heavily influenced by river regulation and engineering works. Upstream changes in climate and land use, and direct measures for flood reduction in the lower floodplains, may again change the amounts of sediments trapped by the lower floodplains in the forthcoming decades. The river is significantly shortened from its natural course due to several canalization projects completed in the 19th and 20th centuries [2]-[4].

## 2.6. Rhine Valley and Delta Soils

Most of Rhine Valley has temperate brown and deep brown soils [8]. Their formation is dependent on hydrologic conditions, vegetation, relief, and human intervention (Figure 6). The Rhine Valley's most productive soils (Figure 5) are developed in alluvial and loess deposits on the floodplain, adjacent terraces, and stream banks. They range from black to extremely fertile brown soil types, and most of them are arable land under cultivation. The finest soils include those in river valley between Mainz, Germany to Basel, Switzerland. Loess covered stream banks and uplands are used for agriculture, viticulture, and grazing. With increasing elevation, soils are suitable only for grazing or forestation. Along The North Sea littoral in the northwest there are some extensive areas of sand, marsh, and mudflats (Figure 7) that are covered with rich soil suitable for grazing and growing crops.

## 2.7. Rhine Falls Geology

The Rhine Falls were formed in the last ice age, approximately 14,000 to 17,000 years ago, by erosion-resistant rocks narrowing the riverbed [2]-[4]. The first glacial advances created today's landforms approximately 500,000 years ago. Up to the end of the Wolstonian Stage approximately 132,000 years ago, the Rhine flowed westwards from Schaffhausen past Klettgau. This earlier riverbed was later filled up with gravel. About 132,000 years ago the course of the river changed southwards at Schaffhausen and formed a new channel, which also filled up with gravel. Part of the Rhine today includes this ancient riverbed. During the Würm glaciation, the Rhine was pushed far to the south to its present course, over a hard Late Jurassic limestone bed. As the river flowed over both the hard limestone and the easily eroded gravel from previous glaciations, formed the waterfall (Figure 1) and (Figure 2). The Rheinfallfelsen, a large rock, is the remnant of the original lime-

stone cliff flanking the former channel. The rock has eroded very little over the years because relatively little sediment comes down the Rhine from Lake Constance.

## 2.8. The Rhine Falls and Rheinfallfelsen

The Rhine Falls (**Figure 8**) is a waterfall (**Figure 9**) located in Switzerland and the most powerful waterfall in Europe [10]-[12]. The falls are located on the High Rhine (**Figure 10**) on the border between the cantons of Schaffhausen (SH) (**Figure 11**) and (**Figure 12**) and Zürich (ZH), between the municipalities of Neuhausen am Rheinfall (SH) and Laufen-Uhwiesen/Dachsen (ZH), next to the town of Schaffhausen in northern Switzerland. The falls are 150 m wide and 23 m high. In the winter months, the average water flow is 250 m<sup>3</sup>/s, while in the summer, the average water flow is 600 m<sup>3</sup>/s. The highest flow ever measured was 1250 cubic meters per second in 1965, and the lowest, 95 cubic meters per second in 1921 [10].



**Figure 8.** The town of Neuhausen am Rheinfall, Switzerland on the Rhine River. Photo Credit: Sergey Chernyanski.



**Figure 9.** The Rhine Falls at the bend in the Rhine River with the town of Neuhausen am Rheinfall, Switzerland in the background. Photo Credit: Sergey Chernyanskii.



**Figure 10.** The main course of the High Rhine River separating Germany and Switzerland. Photo Credit: Sergey Chernyanskii.



**Figure 11.** The High Rhine River valley with the town of Bad Zurzach, Switzerland in foreground. Photo Credit: Sergey Chernyanskii.



**Figure 12.** The town of Bad Zurzach located on the High Rhine River. Photo Credit: Sergey Chernyanski.

### 3. Cultural History

#### 3.1. Cultural History of the Rhine River Valley

By the 6th century, the Rhine was within the borders of Francia. In the 9th, it formed part of the border between Western and Middle Western Francia. By the 10th century, it was fully within the Holy Roman Empire. The county of Holland fell to the Burgundian Netherlands in the 15th century. Holland remained a contentious territory throughout the European wars of religion. The length of the Rhine fell to the First French Empire and its client states after the eventual collapse of the Holy Roman Empire [13]. The Alsace on the left bank of the Upper Rhine was sold to Burgundy by Archduke Sigismund of Austria in 1469. The Upper Rhine was eventually conquered by France in the Thirty Years' War. The numerous historic castles in Rhineland-Palatinate attest to the importance of the river as a commercial route.

Since the Peace of Westphalia, the Upper Rhine formed a contentious border between Germany and France. The long-term goal of French foreign policy, since the Middle Ages, was establishing “natural borders” on the Rhine. The language border was originally much farther to the west. French leaders, such as Louis XIV (**Figure 13**) and Napoleon Bonaparte, tried with varying degrees of success to annex lands west of the Rhine. The Confederation of the Rhine was established by Napoleon, as a French client state, in 1806 and lasted until 1814. Napoleon sold the Louisiana Purchase to the United States for \$15 million to fund this war effort. The Confederation of the Rhine served as a significant source of resources and military manpower for the First French Empire. In 1840, the Rhine crisis, prompted by French Prime Minister Adolphe Thiers's desire to reinstate the Rhine as a natural border, led to a diplomatic crisis and a wave of nationalism in Germany [14].

At the end of World War I, the Rhineland was subject to the Treaty of Versailles (**Figure 14**). This decreed that Rhineland would be occupied by the Allies, until

1935. After that, it would become a demilitarized zone with the German army forbidden to enter. This particular provision of the Treaty of Versailles caused much resentment in Germany. The Allies' troops left Rhineland in 1930. After Adolf Hitler's rise to power, the German army re-occupied it in 1936 which was an enormously popular action in Germany. The Allies may have been able to prevent the German reoccupation. However, Britain and France declined to do so, a feature of their policy of appeasement to Hitler.



**Figure 13.** French forces under Louis XIV cross the Rhine into Netherlands in 1672 [1].



**Figure 14.** Allied soldiers of the Royal Newfoundland Regiment crossing the Rhine in Germany after the end of WWI, December 1918 [1].

In World War II, it was recognized that the Rhine would present a formidable natural obstacle to the invasion of Germany, by the Western Allies (**Figure 15**). During the failed Operation Market Garden of September 1944, the Rhine bridge at Arnhem, immortalized in the book, *A Bridge Too Far* and the film, was a central focus of the battle for Arnhem. Other Operation Market Garden objectives were the bridges at Nijmegen, over the Waal distributary of the Rhine. In a separate operation, the Ludendorff Bridge, crossing the Rhine at Remagen, became famous, when U.S. forces were able to capture it intact. The Germans failed to de-

molish it. This also became the subject of a film, *The Bridge at Remagen. Seven Days to the River Rhine*. The film was about the Warsaw Pact war plan for an invasion of Western Europe during the Cold War.



**Figure 15.** Soldiers of the US 89<sup>th</sup> Infantry Division cross the Rhine in assault boats under German fire as part of Operation Plunder on 24 March 1945 [1].

### 3.2. Development of the Rhine Valley: From Bads to Dams

The Rhine River in Western Europe flows from two small headwaters in the Alps of east-central Switzerland and drains north and west through Netherlands to the North Sea [1]. In 2010, the length of the Rhine declined officially from 1320 km to about 1230 km (Figure 3) and (Figure 4). It has been an international waterway since the Treaty of Vienna in 1815. Approximately, 870 km of the Rhine River is navigable (Figure 16) as far as Rheinfelden (Figure 17) on the Swiss German border. Its catchment area, including the delta area, exceeds 220,000 km<sup>2</sup>.



**Figure 16.** Wine museum and grape growing region. Rudesheim, Germany. Photo Credit: Julialav/Dreamtime.com.



**Figure 17.** Vineyards in Rudesheim Region of Germany. Photo Credit: Jaspe/Dreamtime.com.

The Rhine River is a classic example of a political and cultural boundary line and as an artery of cultural and political unification. The river lands have been memorialized in literature (**Figure 18**) and (**Figure 19**). Since the Roman Empire, the Rhine River has been one of Europe's leading transport routes. Before the 19th century, the goods transported were small in volume. During the second half of the 19th century, the volume of goods increased significantly. The Rhine River became a major axis of industrial production due to cheap water transport, which helped keep the cost of goods down. One-fifth of the world's chemical industries are now manufacturing along the Rhine [1]. River pollution levels have risen; to date, 6000 toxic substances identified in Rhine waters. The Rhine has long been a source of political dissension in Europe but this has given way to international concern for ecological safeguards.



**Figure 18.** Windmills in Kinderdijk, Netherlands. Photo Credit: Reinhardt/Dreamtime.com.

The Rhine River has many old and famous cities (**Figure 20**) on its banks including Strasbourg, France (**Figure 21**); Basel, Switzerland; Cologne (**Figure 3**)



**Figure 19.** Windmills near the Rhine River in Netherlands. Photo Credit: blogspot.com.



**Figure 20.** Starting point for most river cruises of the Rhine. Amsterdam, Netherlands, Photo Credit: Jenifoto406/Dreamtime.com.



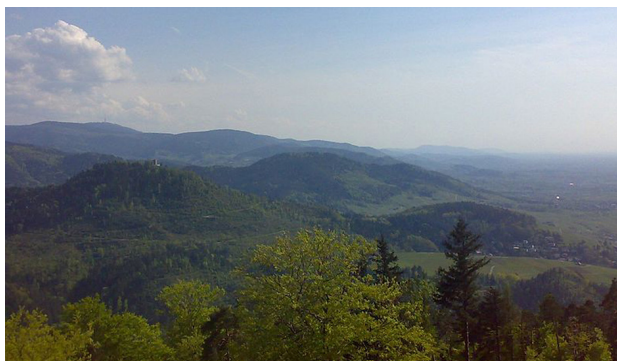
**Figure 21.** Strasbourg, France Photo Credit: Andre Fischer via Wikimedia Commons, CC BY-SA3.0.

and (Figure 4), Konstanz, Worms, and Mainz (Figure 22) Germany. There are also industrial cities such as Ludwigshafen and Leverkusen in Germany that pollute the waters and degrade the scenic attraction of the riverbanks. The middle Rhine, between the German cities of Bingen and Bonn, has steep rock precipices such as the Lorelei crag, and numerous castles which attracts tourists. The Alpine section of the Rhine lies in Switzerland. Below Basel, the river forms the boundary between western Germany and France, as far downstream as the Lauter River. It then flows through German territory to Emmerich and then into Netherlands where it becomes a delta.



**Figure 22.** Confluence of the Rhine and Mosel rivers. Mainz, Germany. Photo Credit: Meinzahn/Dreamstime.com.

The Rhine rises in two headstreams high in the Swiss Alps. The Hinterrhein rises about eight kilometers west of San Bernardino Pass, near the Swiss-Italian border. Below Chur, the Rhine leaves the Alps to form the boundary first between Switzerland and the principality of Liechtenstein and then between Switzerland and Austria [1]. Downstream the Rhine flows swiftly between the Alpine foreland and the Black Forest (Schwarzwald) region (Figure 23). Its pathway is interrupted by rapids and dams. In this stretch, the Rhine is joined by its Alpine tributaries. The Rhine has become more navigable, year around, between Basel and Rheinfelden, since 1934.



**Figure 23.** Black Forest in Germany [11].

Below Basel the Rhine turns northward to flow across a broad, flat-floored valley, some 32 km wide. The river flows between the ancient massifs of the Vosges Mountains and Black Forest uplands and the Haardt Mountains and Odenwald (Oden Forest) upland. Until the straightening of the Upper Rhine, which began in the early 19th century, the river described a series of great loops, or meanders, over its floodplain, and today their remnants, the old backwaters and cutoffs near Breisach (**Figure 24**) and Karlsruhe, mark the former course of the river.



**Figure 24.** Rhine River cruise ships at Breisach. Photo Credit: Travelepeter/dreamstime.com.

The middle Rhine is the most spectacular and romantic reach of the river. In this 145-km stretch, the Rhine has cut a deep and winding gorge between the steep, slate-covered slopes of the Hunsrück mountains to the west and the Taunus Mountains to the east. Vineyards mantle the slopes (**Figure 25**) as far as Koblenz, where the Moselle River joins the Rhine at the site the Romans called Confluentes. On the right bank, the fortress of Ehrenbreitstein dominates the Rhine where the Lahn tributary enters. Downstream the hills recede, the foothills of the volcanic Eifel region lying to the west and those of the Wester Forest to the east. At Andernach, where the ancient Roman frontier left the Rhine, the basaltic Seven Hills rise steeply to the east of the river.



**Figure 25.** Vineyards on sloping stream banks on the Rhine River. Photo Credit: Patricia Krug.

Below Bonn the valley opens out into a broad plain, where the old city of Cologne (**Figure 4**) lies on the left bank of the Rhine. There, the river is spanned by the modern Severin Bridge and the rebuilt Hohenzollern railway bridge. Düsseldorf, on the right bank of the Rhine, is the dominant business center of the North Rhine-Westphalia coalfield. Duisburg, which lies at the mouth of the Ruhr River, handles the bulk of the waterborne coal and coke from the Ruhr as well as imports of iron ore and oil.

The last section of the Rhine lies below the frontier town of Emmerich in the delta region of Netherlands. There, the Rhine breaks up into several wide branches. With the completion of the huge Delta Project in 1986, constructed to prevent flooding in the southwestern coastal area of Netherlands by closing of the branches of the Rhine. Sluices and lateral channels now allow river water to reach the sea. Since 1872, however, the New Waterway Canal, constructed to improve access from the North Sea to Rotterdam, has been the main navigation link between the Rhine and the sea. This canal was built in Europoort, one of the world's largest ports. A major part of this harbor and industrial area (Europoort) is an island isolated by two canals, Calandkanaal and Hartelkanaal. The next and even larger section of Rotterdam's port development, Maasvlakte, which follows Europoort downstream and, unlike Europoort, goes offshore and looks like a man-made peninsula.

The largest city on the Rhine is Cologne, Germany (**Figure 4**), with a population of more than 1,050,000 people. After the Danube, the Rhine is the second longest river in Central and Western Europe, 1230 km with an average discharge of about 2900 m<sup>3</sup>/s. The Rhine and the Danube formed most of the northern inland frontier of the Roman Empire and, since those days, the Rhine has been a vital and navigable waterway carrying trade and goods deep inland. Its importance as a waterway in the Holy Roman Empire is supported by the many castles (**Figure 26**) and (**Figure 27**) and fortifications built along it. In the modern era, it has become a symbol of German nationalism.



**Figure 26.** Marksburg Castle, Brauback, Germany. Photo Credit: Europhotos/Dreamtime.com.



**Figure 27.** Schonburg Castle on hilltop along the Rhine River.  
Photo Credit: Patricia Krug.

### 3.3. Amsterdam (Rotterdam)

Amsterdam, city and port (**Figure 28**) and (**Figure 29**), western Netherlands, located in the Rhine Delta on the IJsselmeer River which connects to the North Sea. It is the capital and the principal commercial and financial center of Netherlands. To the scores of tourists (**Figures 30-32**) who visit each year, Amsterdam is known for its historical attractions (**Figure 33**), for its collections of great art, and for the distinctive color and flavor of its old sections (**Figure 34**), which have been so well preserved. However, visitors to the city also see a crowded metropolis beset by environmental pollution, traffic congestion (**Figure 35**), and housing shortages. It is easy to describe Amsterdam, which is more than 700 years old, as a living museum of a bygone age and to praise the eternal beauty of the centuries-old canals, the ancient patrician houses, and the atmosphere of freedom and tolerance, but the modern city is still working out solutions to the pressing urban problems.



**Figure 28.** Barge on the Rhine River. Photo Credit: Patricia Krug.



**Figure 29.** Lift used to unload ships at the port. Photo Credit: Patricia Krug.



**Figure 30.** Cruise boats along the river near Amsterdam. Photo Credit: Patricia Krug.



**Figure 31.** Cakes at a Bakery in Amsterdam. Photo Credit: Patricia Krug.



**Figure 32.** Store window front in Amsterdam. Photo Credit: Patricia Krug.



**Figure 33.** Church staples in Amsterdam along the Rhine River. Photo Credit: Patricia Krug.



**Figure 34.** A square in Amsterdam with statues. Photo Credit: Patricia Krug.



**Figure 35.** Amsterdam with streetcar service. Photo Credit: Patricia Krug.

Vincent [15] noted that “*Amsterdam is the nominal capital of Netherlands but not the seat of government, which is The Hague. The royal family, for example, is only occasionally in residence at the Royal Palace, on the square known as the Dam, in Amsterdam. The city lacks the monumental architecture found in other capitals. There are no wide squares suitable for big parades, nor are there triumphal arches or imposing statues. Amsterdam’s intimate character is best reflected in the narrow, bustling streets of the old town, where much of the population still goes about its business. While there are reminders of the glorious past—gabled houses, noble brick facades clad with sandstone, richly decorated cornices, towers and churches, and the music of carillons and barrel organs—the realities of life in the modern city often belie this romantic image.*”

“*The inner city is divided by its network of canals into some 90 ‘islands,’ and the municipality contains approximately 1300 bridges and viaducts. Amsterdam is the economic center of Netherlands, and their tradition persists alongside innovation. Although the city has a modern metro system, about one-fifth of the workforce still relies on the time-honored bicycle for transportation. The city continues to be famous for its countless Chinese and Indonesian restaurants and the hundreds of houseboats that line its canals. Since the mid-1960s Amsterdam also has been known for a permissive atmosphere, and it attracts many people seeking an alternative lifestyle. Area city, 165 square km; metro. area, 635 square km Pop. (2008 est.) city, 1,028,603; metro. area, 1,482,676*” [15].

### 3.4. Rhine River a Cradle Civilization

#### 3.4.1. Reformation Periods

The two tragedies, Jan Hus and Anne Frank, took place at the headwaters of the Rhine and in the Rhine Delta. Jan Hus was the most important 15th-century Czech religious reformer, whose work was transitional between the medieval and the Reformation periods and anticipated the Lutheran Reformation by a full century. He was embroiled in the bitter controversy of the Western Schism (1378-

1417) for his entire career, and he was convicted of heresy at the Council of Constance. Jan Hus was burned at the stake and died on July 6, 1415, in Konstanz (Germany) [16]. Another victim who suffered was Anne Frank whose family also suffered for their beliefs, religion, but also ethnicity. What they both had in common was that they kept records while imprisoned, Jan Hus was smuggled a Bible, paper and ink, more than 50 of his letters have survived to this day; Anne Frank's diary, too, survived thanks to the efforts of those who secretly fought the system.

### 3.4.2. Jan Hus

Jan Hus was the most important 15th-century Czech religious reformer, whose work was transitional between the medieval and the Reformation periods and anticipated the Lutheran Reformation by a full century. He was embroiled in the bitter controversy of the Western Schism (1378-1417) for his entire career, and he was convicted of heresy at the Council of Constance. Jan Hus was burned at the stake and died on July 6, 1415, in Konstanz (Germany) (WPJH). Jan Hus ashes were scattered over the Rhine, he can be considered the first significant victim of the Reformation.

### 3.4.3. Anne Frank

Anne Frank House, museum dedicated to German Jewish diarist Anne Frank (Figure 36) located in the canal house (Figure 37) in Amsterdam, Netherlands, where Frank and her family and four other Jewish people hid from Nazis from 1942 until they were betrayed and discovered by the Gestapo in 1944. The museum, which opened in 1960, also includes two adjacent buildings.



Figure 36. Photograph of Anne Frank. Photo Credit [14].

Kay [17] suggested that “*Frank’s father, German businessman Otto Frank, had taken his family—his wife and two daughters—from Germany to Amsterdam before the outbreak of World War II, to escape Nazi persecution. In 1940, he moved his food products business to 263 Prinsengracht, a canal house (Figure 37) and (Figure 38) that was originally built in 1635. The building had a back house, which is now known as the Secret Annex, that was hidden from view by the surrounding buildings, and it was there that the group of eight people secluded themselves, never going out and relying on provisions brought by friends and some of Otto’s*

workers. Though the house was emptied by German troops after the raid, an employee, Miep Gies, was able to salvage the vivid diary that the lively teenage Anne had kept. Gies later gave it to Otto, the only one of the group to survive the extermination camps to which they had been sent. Otto devoted himself to editing and getting the diary published; it was first published in Dutch in 1947. The Anne Frank Foundation was founded, with Otto's cooperation, in 1957, with the aim of preserving the canal house as a museum. The number of visitors was initially overwhelming, and the museum was renovated and expanded in 1999" [17].



Figure 37. Anne Frank house [14].



Figure 38. Canal near the Anne Frank house area [14].

## 4. Results

### 4.1. Management of International Waters

Water is a resource that when shared between neighboring nations requires negotiation not to prevent conflict, but to help conserve it for future use. Studies have shown that disputes over water use do not historically follow a pattern of conflict as much as a pattern of cooperation when negotiations shift from water rights to water needs [14]. A major step towards developing standardized rules for managing waters was the “Convention on the Law of the Non-Navigational Uses of International Watercourses”, which called for equitable, reasonable, and protective

use of waters shared internationally [18]. This requires countries who agreed to these terms to provide a framework that could be applied to their respective and shared waters.

International Commission for the Protection of the Rhine (ICPR) and its contract shows alignment with the UN Convention on international watercourses and has proven effective in its goals for the Rhine and the Rhine Basin. It was necessary for a treaty to come through the countries in the Rhine basin as it provides water based on industrial and agricultural needs and provides drinking water to over 20 million people [14].

On May 21, 1997, the United Nations adopted the “Convention on the Laws of Non-Navigational Uses of International Watercourses. The treaty pertains to ‘*the uses and conservation of all waters that cross international boundaries, including both surface and groundwater*’”. The treaty took 17 years to be ratified, and key countries remained outside the scope of the convention. However, it was an important step in establishing an international law governing water [19].

The Rhine River is one of the most successful examples of the management of an international river via international cooperation in environmental protection. In the 1970s, pollution of the Rhine decreased dramatically [20]. The connections between international cooperation and reduced pollution were not straightforward. Bernauer and Moser [20] concluded “*that international efforts have only modestly and indirectly contributed to pollution reductions, and that, in the Rhine case information approaches to problem-solving have been more effective than formal approaches*”. The researchers [20] “*found the liability frameworks may contribute towards pollution reduction, but, even under favorable conditions, of limited effectiveness*”.

#### **4.2. Past and Present Contamination of the Rhine’s Aquatic Environment**

Being a primary artery draining the most important economic part of Europe, the Rhine historically served as a source-to-sea highway for mobile contaminants and a sink for those less mobile ones which tended to accumulate in bottom sediments and alluvial deposits. The history of abatement of the Rhine’s contamination can be traced back to the initial awareness of the problem which seems to have started in Netherlands, *i.e.* the lower reaches of the river, and dates to the 1920s.

The leading role of Netherlands as the country most dependent on the Rhine’s freshwater resources and the related ecosystem services, on the one hand, and the recipient of the most pronounced cumulative effects of transboundary water and sediment contamination, on the other hand, in studying, coping with and monitoring the contamination problem on a basin-wide scale has been maintained to date. As with other large river basins, contamination of the Rhine was complex and dominated by:

- easily soluble mineral salts, especially sodium and potassium chlorides,
- toxic micropollutants, primarily trace elements and a wide range of organic

compounds,

- the combination of dissolved and colloidal organic matter and nutrients in various forms, affecting, among other things, the oxygen regime of water and redox conditions of bottom sediments,
- suspended solids the presence of which creates unfavorable effects on aquatic biota and water quality, and which are also carriers of sorbed highly toxic pollutants, trace metals, hydrocarbons and others.

Until some time ago, thermal pollution was also relevant for the Rhine which in places was so significant that it affected the microclimatic conditions of the valley and even influenced the behavior of chemical pollutants<sup>3</sup>. As the Rhine drains the countries with high scientific potential, the history of its contamination has long been investigated in detail, which has largely contributed to the success of much of this problem. After the Rhine's contamination became visible to many consumers of its resource-based ecosystem services in the 1920s...1930s, the quality of the river water began to be monitored along with its level.

In parallel with the monitoring, a few organizational and engineering decisions were taken aimed at improving the river basin's health the effect of which was manifested but delayed in time: contamination of the Rhine reached its highest intensity in the late 1960s and early 1970s after which it declined markedly until the late 1980s and has since then fluctuated around the same, relatively low level<sup>4</sup>.

The focus of attention on the composition of the Rhine's contamination has also shifted over the 100 years of monitoring from one group of pollutants to another due to the acquisition or loss of relevance of the respective sources of impact, as well as to the development of methods for quantitative diagnostics of pollutants in the environment.

In particular, in the 1970s...1980s, for heavy metals and arsenic, at that time a priority group of pollutants, the geochemical approach allowed to separate the anthropogenic contribution against the natural levels of presence of each of the elements (e.g. for cadmium it exceeded 99%) and confirmed that already at the beginning of the 20th century contamination with trace metals was a problem in the Lower Rhine. Against the background of a general trend towards the accumulation of a wide range of trace elements in the sediments of the Lower Rhine, peak concentrations of individual elements were observed at different times (but always between the 1950s and 1970s) corresponding to differences in the amounts of their human-induced inflow<sup>5</sup>.

In addition, polycyclic aromatic hydrocarbons (PAHs) and chlorinated aromatics were found to be companions of trace metals and also showed maximum ac-

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<sup>3</sup>Kiss, A. The Protection of the Rhine Against Pollution//Natural Resources Journal. Vol. 25. July 1985. P. 613-637.

<sup>4</sup>Bernauer, T., and P. Moser. Reducing Pollution of the Rhine River: The Influence of International Cooperation//The Journal of Environment & Development. 1996. No. 5(4). P. 389-415.

<sup>5</sup>Salomons, W. and De Groot, A.J., 1978. Pollution History of Trace Metals in Sediments as Affected by the Rhine River. In: Environmental biogeochemistry and Geomicrobiology, Vol. 1. The Aquatic Environment, W.E. Krumbein (Ed.), Ann Arbor Sci. Inc., Michigan, 149-162.

cumulation in the sediments of the Lower Rhine in the 1950s...1970s. Later on, as the share of coal in the energy mix decreased in Western Europe, the export of PAHs to the Rhine valley decreased and the accumulation trends of other organic micropollutants such as PCBs, chlorinated dioxins and other POPs became more relevant<sup>6</sup>.

Since pollutant levels depend not only on the intensity of discharges but also on the flow rate of the river as well as the degree of dilution of the wastewater entering it, the ecological and hygienic effects of contamination and the self-cleaning capacity of the Rhine are directly dependent on its hydrological regime the most problematic condition of which (occurring periodically in autumn) is combined by reducing discharge of snowmelt and glacier water to the Alpine Rhine combined with the low precipitation within the whole basin<sup>7</sup>.

Archives of hydrometeorological observations in the Rhine basin show that the highest recurrence of low-water events took place in the 1920s...1970s, *i.e.* exactly in the periods of registration of the highest concentrations of pollutants. Subsequently, due to water management in the Alpine Rhine and against the background of increasing atmospheric precipitation in the Rhine's basin as a whole, trends in the growth of the Rhine flow have been noted which in the last 25 years have also been supported by the inflow of water from the Danube through the system of hydrotechnical structures connecting the two largest West and Central European rivers<sup>8</sup>.

In contrast to low-water events which are hazardous with the highest levels of pollutants, floods contribute to their distribution including that outside the river channel. More specifically, accumulation of trace metals, PAHs and other sediment-bound pollutants occurs not only in bottom sediments, but also on floodplains where the same chronology is traced: maximum deposition in the interval from 1930s to 1960s and subsequent significant decrease in the intensity of pollutant input with river water (with sorption of dissolved pollutants by soil and subsoil material during infiltration of polluted water) and deposited river sediments<sup>9</sup>.

The example of the Rhine valley clearly demonstrates that even after decades of efforts by several states to improve water quality, a "contamination legacy" persists in the bottom sediments and alluvial soils of the valley. In general, the focus of attention in terms of contamination as the Rhine's aquatic environment im-

<sup>6</sup>Beurskens, J.E.M., *et al.* Geochronology of Priority Pollutants in a Sedimentation Area of the Rhine River//Environmental Toxicology and Chemistry. 1993. Vol. 12. P. 1549-1566.

Winkels, H.J., J.P.M. Vink, J.E.M. Beurskens, and S.B. Kroonenberg Distribution and Geochronology of Priority Pollutants in a Large Sedimentation Area, River Rhine, Netherlands//Applied Geochemistry. 1993. Vol. 8. Suppl. 2. P. 95-101.

<sup>7</sup>Biamond, C. Rhine River Pollution Studies//The Journal of American Water Works Association. 1971. Vol. 63. No. 1. P. 36-40.

<sup>8</sup>Inventory of the Low Water Conditions on the Rhine - International Commission for the Protection of the Rhine (ICPR). Report No. 248. 2018. 92 p.

Belz, J.U. The Runoff Regime of the River Rhine and its Tributaries in the 20th Century Analysis, Changes, Trends//Hydrologie und Wasserbewirtschaftung. 2010. Vol. 54. No. 1. P. 4-17.

<sup>9</sup>Middelkoop H. Heavy-Metal Pollution of the River Rhine and Meuse Floodplains in Netherlands//Netherlands Journal of Geosciences. 2000. Vol. 79. No. 4. P. 411-428.

proves is increasingly shifting to suspended solids and sediments that accumulate historical pollutants which need to be considered when removing sediments during dredging and deciding on their further dumping or onshore management.

At the same time, heavy metals and other eco toxicants accumulated over decades in bottom sediments cannot be regarded as completely deactivated: the example of sediments of the Lower Rhine has shown that, being a predominantly depositing medium with respect to a wide range of pollutants, under certain conditions they can release them into the aquatic environment serving a secondary source of their emission<sup>10</sup>.

And if such substances as PAHs are ubiquitous and continue to arrive (as they are products of fuel combustion) but gradually decompose, there are compounds the use of which is completely banned and their entry into the Rhine Valley, basically stopped, but due to their biochemical stability they continue to circulate in sediments and soils of the valley representing both ecological and health hazard. An example of this group of pollutants is hexachlorobenzene (HCB) whose sources of contamination in the Higher and Upper Rhine ceased discharging in the 1980s, with the presence of this substance still having a significant effect on the quality of dredged material from Rotterdam harbor and therefore needs special attention and response measures<sup>11</sup>.

Naturally, the level of chemical contamination and the resulting ecotoxicity of the Rhine sediments must be taken into account when planning measures for the management of this material excavated from dredging sites, significantly limits the possibilities for its use (e.g. in construction or landscaping) and requires measures to prevent further spread of contaminants<sup>12</sup>.

Observations on the composition of the Rhine's water phase and suspended solids continue unabated, and according to the published data, in addition to the heavy metals traditionally present (Cr, Cu, Zn, Cd, Hg and Pb), the need to monitor pollutants such as La, W and Te, also originating from predominantly anthropogenic sources, has been added.<sup>13</sup> A special focus was also recently put on the occurrence and distribution of Ga, Ge, Nb, In, Te, REE, and Ta: based on the calculation of geo-accumulation indices, distinct enrichments along the Rhine were observed for these technology critical elements<sup>14</sup>. In addition, the problem of con-

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<sup>10</sup>Salomons, W., N.M. de Rooij, H. Kerdijk, J. Bril. Sediments as a Source of Contaminants?//Hydrobiologia. June 1987. P. 13-30.

<sup>11</sup>Heise, S., and U. Forstner. Risks from Historically Contaminated Sediments in the Rhine Basin//Water, Air, & Soil Pollution. December 2006. 18 p.

<sup>12</sup>Vollmer S., and E. Goeltz. Sediment Monitoring and Sediment Management in the Rhine River//Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ., 2006. P. 231-240.

Burgos, R.P., *et al.* Old Contaminated Sediments in the Rhine Basin During Extreme Situations. Synergy project Water Quality and Calamities. Report ID: Q4453. Deltares, 2008.

<sup>13</sup>Van der Perk, M., and A.E. Vilches. Compositional dynamics of suspended sediment in the Rhine River: Sources and Controls//Journal of Soils and Sediments. 2020. Vol. 20. P. 1754-1770.

<sup>14</sup>Klein O., T. Zimmermann, L. Hildebrandt, and D. Pröfrock Technology-Critical Elements in Rhine sediments: A case study on occurrence and spatial distribution//Science of The Total Environment. Vol. 852. December 2022.

tamination of water and sediments by microplastics deposited on floodplains during each flood is becoming increasingly recognized<sup>15</sup>.

As climate change leads to an increase in the frequency of major floods, the problem of secondary mobilization of historical contamination is also relevant for the Rhine Valley. In particular, the catastrophic flooding of 2021 in Germany has raised the challenge of developing specific action plans to address contamination risks caused by the flood itself, as well as to identify and eliminate those hotspots of historical contamination that may be present within the area of new flood events<sup>16</sup>.

To summarize the above, the priority contamination aspects included in The Rhine 2040 Programme, which aims at sustainable management of the river's catchment area, are as follows<sup>17</sup>:

- the introduction of nutrients into surface waters and groundwater,
- the influx of micropollutants into waters from municipal wastewater collection and treatment systems, industry and commerce and agriculture,
- the quality of the sediments in the mainstream, and
- the entry of waste, in particular plastic, into the body of the Rhine's water.

### 4.3. Microplastic Pollution of the River Rhine

The Rhine, between Rotterdam and Basel, has one of the highest microplastics pollution levels in a river. Mani *et al.* [20] reported "*Microplastics, smaller than 5 mm, are found in all water bodies. They occur as pellets for cleaning and care products, as intermediate production in plastic production, or from fragmentation of plastic debris. They contribute to 'great garbage patches' in oceans. Microplastics are ingested by many organisms, from baleen whales to protozoa. Approximately 80% of the marine plastic comes from rivers including the Rhine. The Rhine's microplastics are among the highest in the world. Researchers calculated that the Rhine contributes a daily load of more than 191 million plastic particles to the North Sea. This corresponds to 25 to 30 kg/day or 10 tons/year. These billions of plastic items can be ingested by organisms and have a negative effect on the health of the organism and may enter the food chain*".

## 5. Conclusions

The primary objective of this paper was to document the natural and anthropic risks to the Rhine River and Delta including navigation, stream capture, settlement, invasions, and trade. Environmental risks include pollution, contamina-

<sup>15</sup>Rolf, M., *et al.* Multi-Method Analysis of Microplastic Distribution by Flood Frequency and Local Topography in Rhine Floodplains//Science of The Total Environment. Vol. 927. June 2024. 15 p.

<sup>16</sup>Bellanova, P., J. Schwarzbauer, and K. Reicherter. Inventory of Aqueous and Sediment-Associated Organic Pollutants Released by the 2021 Flood in the Vicht-Inde Catchment, Germany//Environmental Sciences Europe. 2024. 36: 110. 23 p.

<sup>17</sup>The Rhine and Its Catchment: Sustainably Managed and Climate-Resilient/International Commission for the Protection of the Rhine. The 16th Rhine Ministerial Conference. February 13, 2020, Amsterdam.

tion, industrial and urban wastewater, overfishing, threats to food supply, urban development, channelization, dams, shoreline erosion, and flooding. An entire set of Rhine-based ecosystem management services has been developed in the context of international relations. This includes navigation, water withdrawal for various purposes, wastewater discharge, extraction of aquatic bioresources, agriculture within the floodplains and river terraces, and finally the river's role as a national boundary (which was gradually the river border has evolved from a "fence" to a "bridge") (and therefore, physically, over 100 bridges have been constructed across Rhine). The Rhine River and Delta represent an example of how successful and effective international cooperation on natural resource management can and should be conducted. The most critical area remains the delta, as continuing sea level rise increases the vulnerability of this densely populated area and requires ever-new engineering solutions.

The Rhine became a central European trade route, most of which is navigable. The Rhine River flows into Netherlands and becomes a delta. The Rhine was important as a waterway in the Holy Roman Empire and is supported by the many fortifications and castles built along it. The long-term goal of French foreign policy, since the Middle Ages, was establishing "natural borders" with Germany on the Rhine. The language border was originally much farther to the west. In the modern era, it has become a symbol of German nationalism. The Rhine has captured the Danube headwaters via limestone sinkholes and underground river flows. This is a classic example of stream or river capture. The Rhine has a watershed that includes parts of 10 countries which made it difficult to address historic navigation, flooding, and trade challenges. The Rhine Delta, the second largest in Europe and located in Netherlands, extends into the North Sea. The Rhine Delta is one of the most urbanized major deltas in the world. One-fifth of the world's chemical industries are now manufacturing along the Rhine. The Rhine, between Rotterdam and Basel, has one of the highest microplastic pollution levels in a river. These billions of plastic items can be ingested by organisms that hurt the health of the organism and may enter the food chain. The natural and anthropic risks to the Rhine River include settlement, invasions, navigation, and trade. Environmental risks include pollution, industrial and urban wastewater, over-fishing, a threat to food supply, urban development, locks and dams, shoreline erosion, and flooding.

### Conflicts of Interest

The authors declare that there is no conflict of interest.

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