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Environmental Impact of Kakhovka Dam Breach and Chernobyl Nuclear Power Plant Explosion on Dnieper River Landscape

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Abstract

The Dnieper River headwaters are in Russia's Valdai Hills and the river flows south to the Black Sea. The Dnieper River provides a waterway in which to transport goods to and from various European nations. In addition, the dams on the river provide hydro power. There are approximately 2260 km of Dnieper waterways in Russia, in Belarus, and within Ukraine. The Dnieper River has numerous urban centers including Smolensk in Russia, Mogilev in Belarus and Kiev and Zaporizhzhya in Ukraine. The worst nuclear accident in history unfolded, in the Dnieper River watershed, in northern Ukraine as a reactor at the Chernobyl nuclear power plant exploded and burned. After an accident, such as Chernobyl, radionuclide contaminated bodies of water via direct deposition from the air, discharge as effluent or indirectly from catchment basin washout. When radionuclides contaminate large bodies of water, they are quickly dispersing and accumulate in water bottom sediments, benthos, aquatic plants, and bottom feeding fish. The main pathways to humans are through contamination of drinking-water, from use of water for irrigation of food crops, and consumption of contaminated fish. Kakhovka Dam on the Dnieper River was destroyed during the Russian-Ukraine conflict and the dam needs to rebuild as soon as possible. Perhaps lessons learned by the US Army Corps of Engineers (USACE), after using TNT to blow up the Birds Point front line levee on the Mississippi River in May of 2011, can be applied to the man-induced 2023 Kakhovka Dam breach. The Birds Point man-induced levee breaches and subsequent flooding of farmland resulted in the loss of the 2011 crops and damaged the future soil productivity. The strong current and sweep of the water through the three man-induced levee breaches on the New Madrid floodway levee created deep gullies, displaced tons of soil, and damaged irrigation equipment, farms, and homes. The New Madrid floodway agricultural lands were restored, and the environmental damages were mitigated. The Kakhovka Dam destruction caused widespread flooding which affected settlements and farmland across the Dnieper watershed. The presence and breach-induced redistribution of Chernobyl-derived nuclides is an additional condition not present at the New Madrid man-induced levee breach. Four canal networks have become disconnected from the feeder reservoir. The canals were the source of drinking water for 700,000 people living in southern Ukraine. The Kakhovka canals also provided irrigation for vast areas of farmland. The water loss from the canals adversely affected food production in the region. The primary objectives of this paper are to assess lessons learned by the USACE and apply them in Ukraine to help restore and manage the Dnieper lifeline and watershed.

Keywords

Dnieper River, Ukraine, New Madrid Levee, TNT, Chernobyl, Kakhovka Dam, 137Cs, Black Sea, Kiev

1. Introduction

1.1. Dnieper River

The Dnieper River headwaters are at a 220 m elevation in Russia's Valdai Hills and the river flows south to the Black Sea (**Figure 1**). The 2180 km river and watershed are in western Russia, Belarus, and Ukraine. The Dnieper River has three sections, the lower portion is between Zaporizhzhya and the delta (**Figure 2**) at the Black Sea [1]. The middle portion is the area between Kiev and the Ukrainian city of Zaporizhzhya and the upper portion extends from Kiev (**Figure 3**) to the headwaters in western Russia. The Dnieper River provides a waterway in which to transport goods to and from various European nations. In addition, the dams on the river provide hydropower [2]. Approximately, 480 km of the waterways are in Russia, 690 km in Belarus, and 1190 km within Ukraine. Only the Danube, Ural and Volga rivers in Europe are longer than the Dnieper River.

The Dnieper has a 505,000 km^2 watershed with 32,000 tributaries. The Dnieper has numerous urban centers including Smolensk in Russia, Mogilev in Belarus and Kiev (Kyiv) and Zaporizhzhya in Ukraine. The Dnieper watershed consists of broad lowlands, a forest area, and a forest area, forest-steppe, and steppe areas. The basin is covered with morainic, fluvioglacial, and a variety of loess-like deposits. The steppe is covered with windblown silt (loess). In some places, where the basin borders the Bug and the Western Dvina rivers, there are swampy flat areas.

1.2. Dnieper River Watershed Natural Resources

The source of the Upper Dnieper is the sedge bogs of the Valdai Hills https://en.wikipedia.org/wiki/Valdai_Hills in central Russia, at an elevation of

220 m [3]. For 115 km of its length, it serves as the border between Belarus and Ukraine. Its estuary used to be defended by the strong fortress of Ochakiv [4]. The water resources of the Dnieper basin compose around 80% of the total for Ukraine [5].

The lower Dnieper basin (**Figure 2**) lies in the Chernozem steppe area (**Figure 3**) within the Black Sea Lowland, which has now been completely cultivated. The grassy steppe vegetation has been preserved only in old ravines and gullies and in the nature reserves and preserves. There is wormwood-fescue (Festucion valesiacae) and (Festucion valesiacae) vegetation of the semiarid type, in chestnut brown soil mixed with saline solonetz and solonchak soils, near the Black Sea. The lower Dnieper passes through a region of insufficient moisture, where irrigation is utilized.

On the southern portion of the middle Dnieper, the river cuts through the Ukrainian crystalline massif and flows for 90 km in a narrow, almost unterraced valley bounded by high, rocky banks. The Dnieper Rapids, which for centuries prevented continuous navigation, were once located there. The rapids were flooded by the backwaters of the Dnieper hydroelectric power station dam, above Zaporizhzhya, which raised the level of the river by 40 m.

Figure 1. Map showing the location of the Dnieper and Dniester Rivers. Photo Credit: mappingmemories.ca.

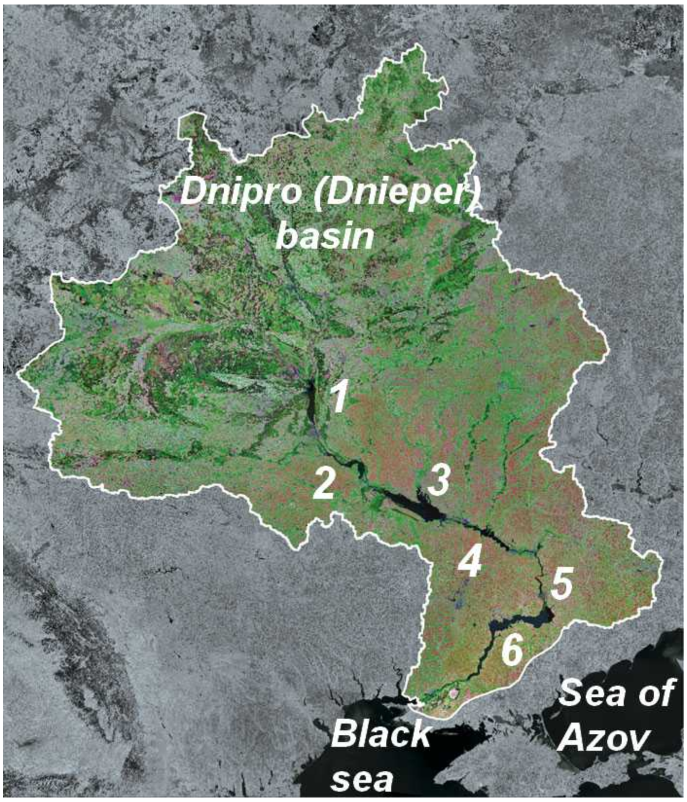

Figure 2. Dnieper (Dnipro) basin flowing into the Black Sea. Photo Credit: Reddit.

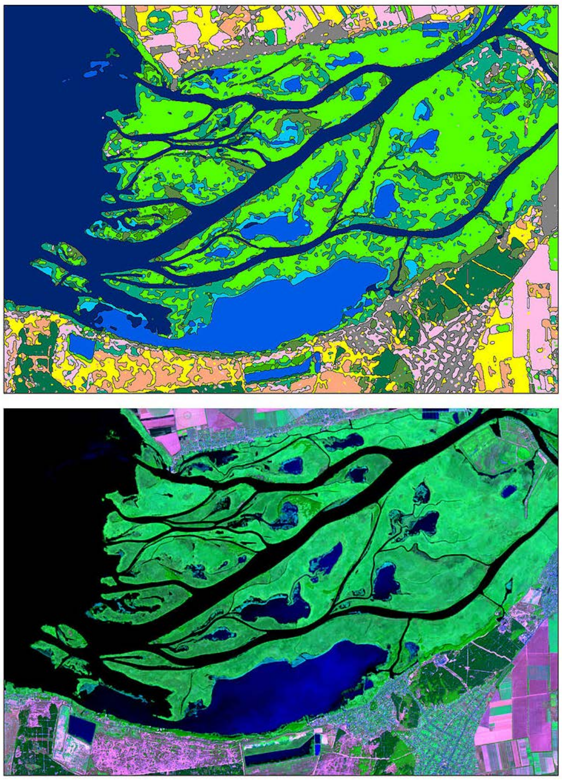

Figure 3. The Dnieper River delta. Thematic map (upper) and false-color IR from satellite images of the Dnieper delta. 8 Aug. 2015. Photo Credit: Anastasiya Tishaeva.

1.3. Hydrology of the Dnieper River

Since 1818 the Dnieper River flow characteristics have been studied. Using high water marks, the maximum discharge rates have been extended back 250 years. Spring snowmelt in the river's upper basin provides much of the annual discharge. About 60 percent of the annual runoff occurs from March to May. The period of stable ice on open water begins in the upper Dnieper at the beginning of December and in the lower Dnieper at the end of December. Thaw starts at the beginning of April in the upper course and in early March in the lower course. The average annual flow at the river mouth (**Figure 4**) is about 1670 cubic meters per second with considerable yearly variability. Each year the river carries an average of 8.6 million tons of dissolved matter to the Black Sea (**Figure 5**). The volume of suspended sediments carried by the Dnieper into the Black Sea was significantly reduced by the creation of the cascade of reservoirs.

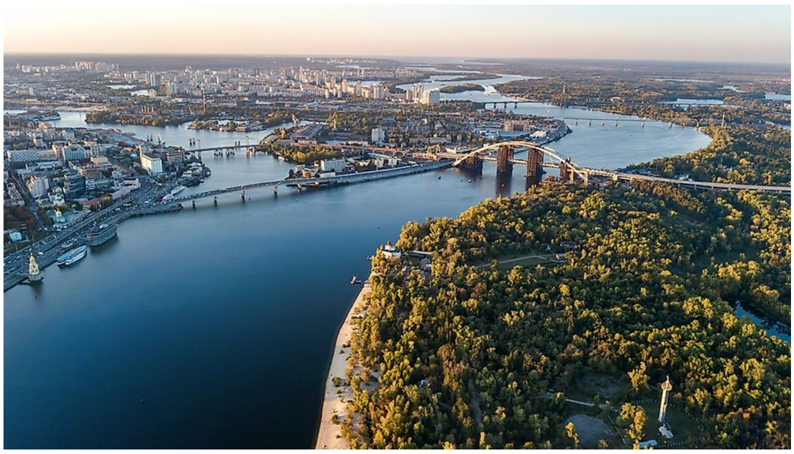

Figure 4. Four motor bridges and one railroad bridge over the Dnieper River in Kiev, Ukraine. Photo Credit: Encyclopedia Britannica, Cavan iStock/Getty images.

Figure 5. Ukraine map showing the location of the Dnieper River and Chernobyl. Photo Credit: In the Public Domain.

1.4. Climate

The mean annual precipitation north of Kiev in the upper Dnieper basin is about 710 mm. The precipitation average for the entire basin is about 68.5 cm, with about half falling, as rain, during the fall and summer. The climate of the Dnieper watershed is temperate and much damper and milder than Don and Volga basins located at a similar latitude. From northwest to southeast the continental nature of the climate increases.

1.5. Plant and Animal Life

The Dnieper has diverse aquatic fauna and flora. In its upper section, the plankton consists mainly of diatom and protozoal, rotifers, algae and *Bosmina.* Blue-green algae come from the mouth of the Pripet (Pripyat) (**Figure 1**). In its lower section, the number of plankton decreases sharply under the influence of the reservoirs. More than 60 species of fish live in the Dnieper. Commercially important species include barbel, carp, pike, roach, chub, ide, rudd, tench, aspius, alburnum, golden shiner, goldfish, perch, catfish, pike perch, burbot, and ruff. In the spring the lower Dnieper serves as a habitat for semi-migratory and migratory fish (sturgeon, herring, roach, and others). The reservoirs have been stocked artificially with fish of commercial importance, including carom whitefish, golden shiner, pike, and perch. The cascade of dams, shipping, fish farming, and several other anthropogenic factors have created conditions favorable for invasion of aquatic organisms in the Dnieper basin.

1.6. Dnieper

History and Economy

A system of river routes developed along this waterway in the 4th to 6th century CE as a "*route from the Varangians to the Greeks*". The waterway connected the Black Sea with the Baltic and linked the Slavs with both the Baltic and Mediterranean peoples. The Dnieper basin has been populated since ancient times. The basin was of central importance in the history of the peoples of Eastern Europe, especially in the founding of the ancient Kievan Rus. Half of the Dnieper, about 1,100 km, borders or passes through Ukrainian territory. The Dnieper River is a national symbol for the Ukrainians just as is the Volga River [6] for the Russians. The Greek historian Herodotus (5th century BCE) recorded the first historical information about the Dnieper. The river was later mentioned by the ancient writers Strabo and Pliny the Younger. In the 2nd century CE, the river was first depicted on a map drawn by Ptolemy. Early in the 18th century, instrument surveys of the Dnieper were made.

Much work was undertaken for the multipurpose exploitation of the Dnieper's water resources by the Soviets. In accordance with the Soviet Union's electrification plan, the river's first hydroelectric power station was completed, in 1932, at Zaporizhzhya in the region of the rapids. It was the largest power station in Europe until the 1950s when huge power stations were constructed on the

Volga [6]. During World War II, the Dnieper Hydroelectric Station near Zaporizhzhya was completely destroyed by the German Army. It was rebuilt in 1948 with increased capacity. Dams with hydroelectric power stations and reservoirs were built on the Dnieper at Kaniv (1973), Kiev (completed 1966), Dneprodzerzhinsk (1965), Kremenchug (1961), and Kakhovka (1958). Their construction solved many problems. The irrigation of arid lands in southern Ukraine and Crimea has been made possible. The chronic water shortages in the Donets Basin and Kriviy Rih industrial regions have been solved. A continuous deepwater route from the mouth of the Pripet to the Black Sea (**Figure 5**) has been created. In southern Ukraine and Crimea irrigation of arid lands was made possible.

The passage of modern vessels was made possible by navigable locks. The principal cargoes are ore, mineral building materials, coal, grain, and lumber. The Kriviy Rih region is supplied with water from the Kakhovka Reservoir by means of the Dnieper-Kriviy Rih Canal. The 1971 North Crimea Canal originates in the reservoir. The canal, 400 km long, was designed for irrigation of the steppes of the Black Sea lowland and northern Crimea.

The estuary wetlands have been seriously damaged by reduced discharge and pollution. Damming and diverting the Dnieper waters radically altered its natural ecology and hydrology. Upstream access for anadromous fish has been reduced by seasonal flow variations and dams as physical obstacles. Effluents from industry and cities as well as from increased agricultural runoff have caused pollution. The evaporation from reservoirs and diversion of water for irrigation have lowered the annual outflow of the river by some 20 percent.

The restoration and mitigation lessons learned from man-induced (USACE) New Madrid levee breaches in the U.S. should be applicable to restoration and mitigation efforts needed because of the man-induced Kakhovka Dam breach, during the Russia-Ukraine conflict, and subsequent environmental damages to the Dnieper River Valley. The primary objectives are to assess lessons learned from man-induced New Madrid levee breaches in the United States and to apply them to mitigate, restore, and manage the Dneiper River lifeline and watershed.

2. Study Sites: Damages and Environmental Consequences of Man-Induced Levee Breaches in the United States and Ukraine

2.1. Case Study 1: New Madrid Floodway Man-Induced 2011 Levee and Dam Breaches in United States

In the aftermath of the deadly 1927 Mississippi and Ohio River flood, USACE designed the New Madrid Floodway project, located in the state of Missouri, as part of a larger Mississippi River Basin plan to control flooding and manage the river. The frontline levees and floodwalls contain Ohio and Mississippi rivers at the confluence when agricultural and urban land is threatened by floodwaters [7]. The New Madrid Floodway (**Figure 6**) and border levees (**Figure 7**) were built under the authority of Flood Control Act of 1928 (70th US Congress, Session 1 Chapter 596, enacted May 15, 1928). The Floodway is between 6.4 km and 16.1 km wide and is approximately 53.1 km long. The Floodway is enclosed by setback and frontline levees, except for a 457 m gap at the lower end. This gap serves as a drainage outlet which allows flood backwaters to re-enter the Mississippi River. The 24 km long frontline levee section connects the two plugs [8] including a 17.7 km long upper fuse plug and an 8 km long lower fuse plug. The frontline levee forms the eastern boundary of the Floodway. It was constructed to protect the Floodway until the Mississippi River reached the 16.8 m stage, at which time the floodwater would naturally overtop the frontline levee. Only a very small breach occurred during the flood of 1937.

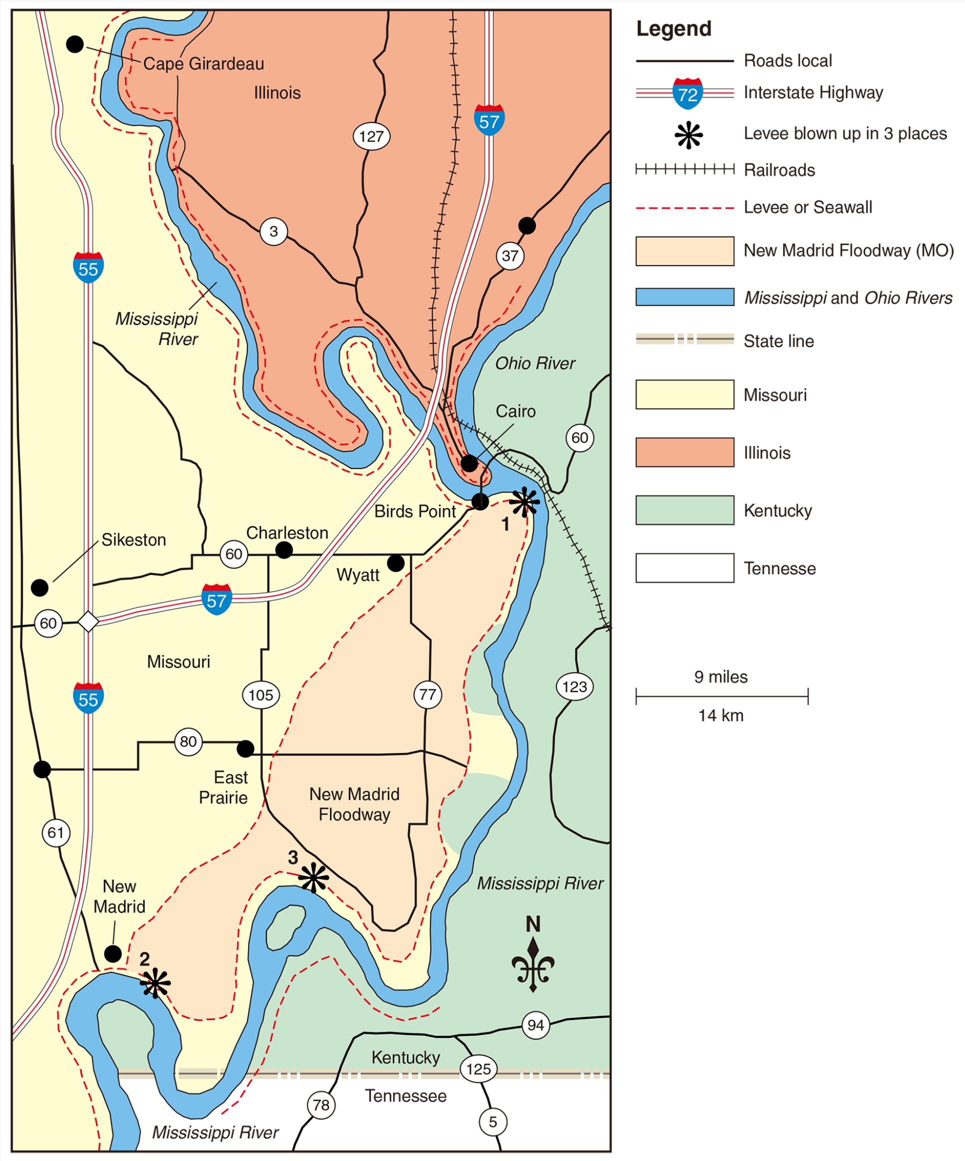

Figure 6. The Ohio and Mississippi rivers confluence at Cairo, Illinois, to become the Mississippi River. The floodplain to the west of the Mississippi River as it flows south from Cairo to New Madrid, Missouri, is a natural overflow spillway or floodway to store excess water when the rivers are above flood stage.

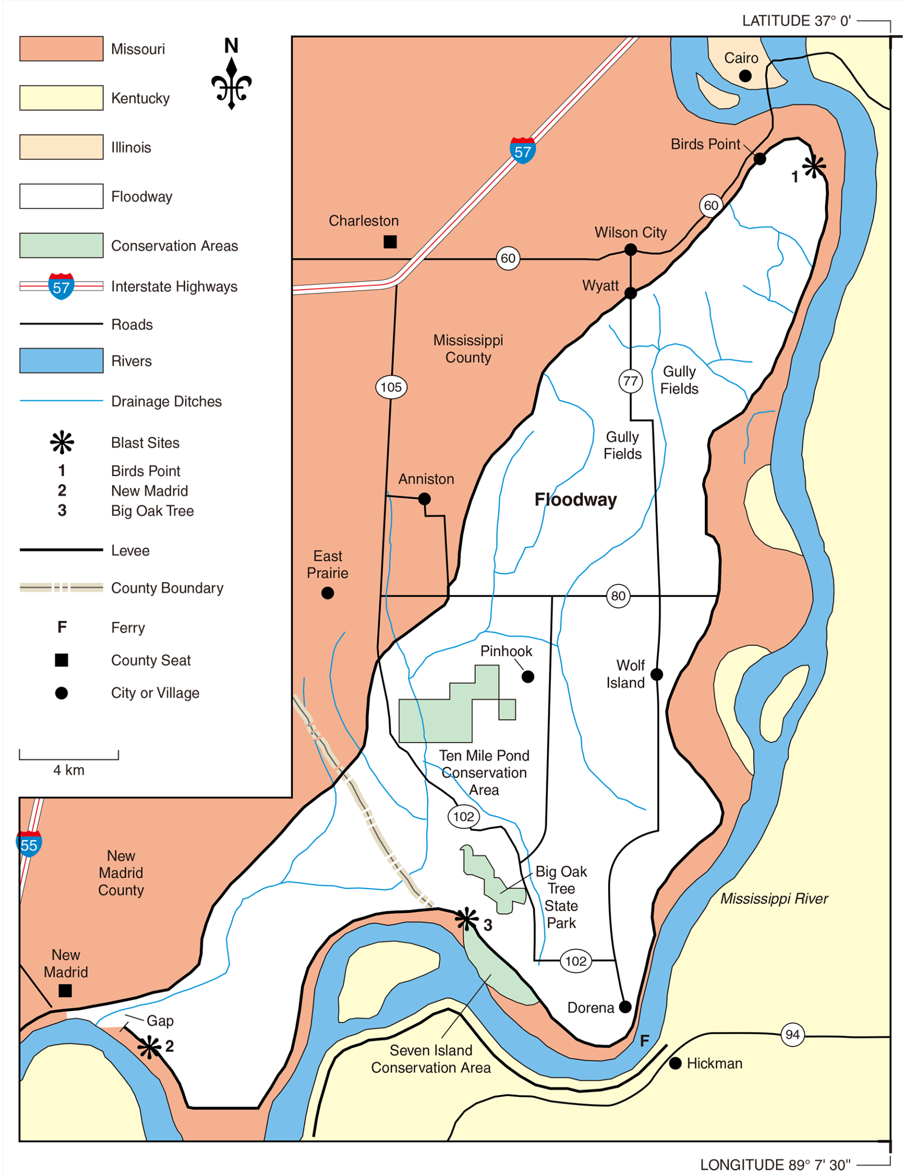

Figure 7. The Birds Point-New Madrid Floodway is located in Missouri just south of Cairo, Illinois and the confluence of the Ohio and Mississippi Rivers.

The 57.9 km long setback levee goes from Birds Point, Missouri, to New Madrid, Missouri (Figure 6). The USACE obtained easements with the landowners in the 53,824 ha of the New Madrid Floodway in 1928, which gave them the right to pass floodwater into and through the New Madrid Floodway and temporarily store floodwater in the basin. Congress authorized the modification of the New Madrid Floodway operational plan in the Flood Control Act of 1965 (Public Law 89-298, 89th US Congress, enacted October 27, 1965) [8]. The plan called for raising the upper and lower fuse plugs to 18.4 m, the frontline levee to 19.1 m, and the setback levee to 20 m. The Floodway plan also called for artificial crevassing (breaking or breaching) of the levee by means of explosives on the upper fuse plug section of the frontline levee when the river stage (Figure 8) was at

Figure 8. The Birds Point levee breach created a crater lake that extended many meters through the levee.

or above 17.7 m on the Cairo gauge with a prediction that stages would exceed 18.3 m. The plan envisioned natural breaching in the lower fuse plug in the event of a flood of the magnitude of the 1937 flood. The levee system's construction was significantly improved by raising and strengthening the frontline levee after the approval of the 1966 plan [8].

2.1.1. Authority to Pass Floods through the New Madrid Floodway

Olson and Morton [8] found "*The* 1965 *Flood Control Act gave the USACE the authority to pass floodwaters through the New Madrid Floodway. The USACE, armed with the power of eminent domain, obtained modified flowage easements within the Floodway lands to permit the expected artificial breaching and the resultant inundation of a major flood. The Birds Point upper fuse plug levee was designed to be blown up with explosives in the event of a great flood. No such event happened after* 1966, *not even during the floods of* 1975 *and* 1979. *The USACE adopted a modified plan in* 1983 *calling for the artificial breaching of both the upper* (*near Birds Point*) *and lower* (*near New Madrid*) *fuse plugs and the middle section of the frontline levee south of Big Oak Tree State Park, which is in Mississippi County and adjacent to New Madrid County in Missouri. Landowners in the New Madrid Floodway filed suit against the USACE* (*Story vs. Marsh*) *in opposition to the* 1983 *artificial breaching plan of the frontline levee between the two fuse plug sections. The Eastern District Court of Missouri ruled in favor of the landowners and enjoined the Secretary of the US Army and subordinates from artificially crevassing* (*breaching*) *the frontline levee*".

"*This case law became the legal precedent used by the Federal court system in* 2011 *to decide a last-minute appeal by landowners in the Floodway to prevent the Corps from blowing up the frontline levee once the Cairo levee and floodwall floodwaters reached* 17.7 m *with a forecast of* 18.3 m *or higher peak. Consequently, floodwaters continued to rise through April and until* May 1, 2011, *when the Supreme Court affirmed the USACE right to blow up parts of the frontline levees and pass water into and through the New Madrid Floodway and on basin soils* (*Caruthersville very fine sandy loam, Commerce silty clay loam, Dundee silt loam, and Forestdale silt loam*)*. The amount of temporary water storage* (*at initial depths from* 1.8 *to* 3.7 m) *and pass-through water in the New Madrid Floodway was* 25 *to* 28 times *greater than what could have been stored in the Cairo and Future City, Illinois, areas, and adjacent agricultural areas of Illinois if the Cairo and Future City floodwalls or levee system were naturally breached*" [8].

2.1.2. Cairo

Olson and Morton [7] [9] noted "*In* April 2011, *the Ohio River began flooding farmland and cities from Pennsylvania to Illinois that were not protected by levees. The USACE had realized as early as March that the torrential rains and heavy snow melt across the Upper Midwest were setting up the Mississippi River Basin for an epic flood year* [7] [9]*. By late April, lakes and reservoirs along the Wabash and Ohio rivers* (**Figure 9**) *were filled and cities without levees, such as Metropolis, Illinois, had lower sections covered by floodwaters. Cairo, Illinois, and many of the cities on the lower Mississippi River were protected by levees. The levee is a massive earthworks designed to contain floodwater. It has a flat crown at least* 2.4 *m wide with* 3:1 *sloped side* (*a levee* 9.1 m *high would be at least* 57.3 m *wide, including* 2.4 m *wide crown plus two sides, each* 27.4 m *wide*)*. The height of the levee changes the force of the river; a levee as high as a three- or four-story building can explode with the same power and suddenness of a dam bursting* [7] [9]*. The greatest danger to levy failure is constant water pressure against the levee. The weight of the river pushes water underneath the levee, creating boil sand undermining the strength of the levee and its capacity to hold water. By the end of April, the floodwaters on the levee and floodwall at Cairo, Illinois, had reached* 18.6 m *and were rising. Floodwaters were starting to put significant pressure on the Cairo floodwall and levee system with some seepage or sand boils. The USACE decision to blow up Birds Point levee on the Mississippi River and flood agricultural lands in the New Madrid Floodway, Missouri, on May* 2, 2011, *to protect the approximately* 1 million *hectares of agricultural lands down river and to protect the city of Cairo, Illinois* (**Figure 6**)*, was a calculated risk built on a growing body of river science and prior flooding experiences [8]. The decision was a difficult and complex engineering problem with significant social and political trade-offs between loss of human lives and loss of properties in urban and rural areas*" [7] [9].

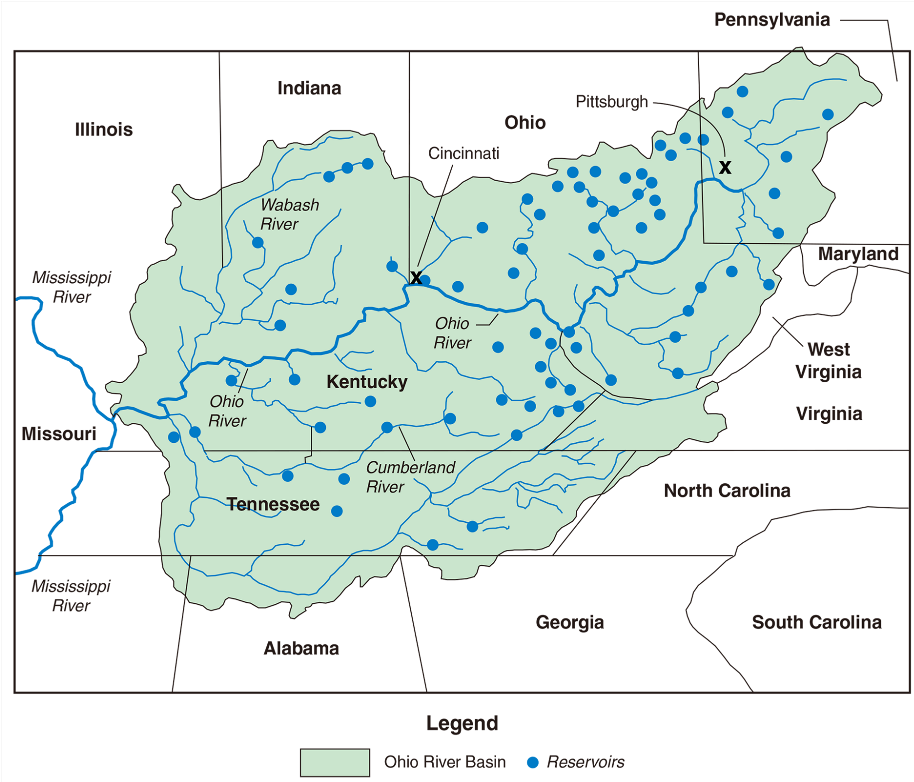

Figure 9. The location of all the reservoirs in the Ohio River watershed.

2.1.3. USACE Use of TNT to Induce Three Levee Breaches

Olson and Morton [8] found "*The induced breach at Birds Point, Missouri, the first explosion site* (**Figure 8**) *and flooding of the New Madrid Floodway and basin on May* 2, 2011, *resulted in no loss of life thanks in part to the US National Guard sweep of the area to make sure the people living and working in the Floodway were evacuated* [8]. *The force and impact of the floodwater on the* 470 km^2 *of the Floodway may have been greater than projected in the* 1983 *Corps of Engineers operational plan. The Floodway was subjected to rapidly moving floodwaters which were initially* 1.2 m *deeper than would have been released if the fuse plug was blown when the Cairo levee was at* 17.7 m. *There was severe damage to most of the* 200 *or more buildings, including homes, which were exposed to* 0.9 *to* 1.8 m *of flowing water and then partially submerged in* 1.8 *to* 3 m *of floodwater. Water pressure caused loss of the lower one-third to one-half of entire walls, damaged most wooden floors, and in some cases, destroyed structures* (**Figure 10**)."

"*On May* 3, 2011, *the lower plug levee was blown up near New Madrid, Missouri, the second explosion site* (**Figure 11**) *to begin the return of the stored floodwater back into the Mississippi River. However, the Mississippi River was still too high to allow a quick drop in the floodwater in the New Madrid Floodway. The USACE planned to blow up the frontline levee in two places using* 150 tons *of TNT near Big Oak Tree State Park in Missouri, the third explosion site* (**Figure 11**), *on May* 4, 2011, *but weather and shortage of TNT delayed the third* *explosion until May* 5, 2011. *It appears for the next few days that the Mississippi River floodwater at the third breached levee site flowed out for days before it flowed back in since the Mississippi River remained above flood stage. Evidence of the inward flow includes a crater lake adjacent to the west side of the frontline levee and a sand deposit west of the frontline levee rather than to the east* [10]. *Local farmers reported that Mississippi River water did flow out initially on May* 5, 2011, *but* 14 *days later started to flow rapidly in through this* 3*rd frontline levee breach, creating a* 6.4 ha *lake, gullies, and a thick* 100 ha *sand deltaic deposit. Over the next few weeks, the New Madrid Floodway continued to drain through the New Madrid breach, and the floodwater in the Floodway basin dropped to between* 0.6 *and* 2.1 m *depending on the elevation of bottomland soils; however,* 0.9 *to* 2.1 m *of floodwater remained and covered both cropland and pastureland*" [8].

Figure 10. One of the 80 homes in the floodway was damaged by 2 to 3 m of floodwater in 2011.

Figure 11. A crater lake was formed at the Big Oak Tree frontline levee when the fuse plug was blown and floodwaters rushed into the floodway.

2.1.4. Birds Point Man-Induced Levee Breaches

The deliberate breaching of the Birds Point levees (**Figure 8**) (**Figure 11**) in the New Madrid Floodway downriver from Cairo in May 2011 was a planned strategy of the United States Corps of Engineers (USACE) to prevent levee failures and to reduce water pressure where harm to human life might occur. The induced breach and the flooding of 53,824 ha of Missouri farmland resulted in the loss of 2011 crops and damage to future soil productivity. The strong current and sweep of water through the Birds Point, Missouri breach damaged irrigation equipment, farms, and home buildings and created deep gullies, and displaced tons of soil.

Olson and Morton [7] [8] determined "*The decision to blow up the Birds Point fuse plugs and frontline levees had significant consequences for rural Missouri landowners, farmers, and residents in the New Madrid Floodway. The impact of the floodwaters on the Floodway appears to have been greater than anticipated in part because of the delay in opening the Floodway due to legal action. When the USACE was given permission by a U.S. Supreme Court justice to open the Floodway, the Mississippi River was* 1.2 m *higher than planned for, and the initial additional force and depth of floodwater caused more damage to buildings and more deep land scouring than was predicted. Impacts included the loss of the* 2011 *wheat crop and of crop production from perhaps* 8094 *to* 12,146 ha *of poorly drained clayey soils that were not replanted in* 2011*. Most of the farmland in Floodway dried out sufficiently to permit fall planting of wheat. The Floodway was not sufficiently dry until the spring of* 2012 *to allow the planting of corn and soybeans. It is not clear how much of* 2011 *farm income replacement was, from flood insurance, which occurred since not all Floodway farmers had crop insurance*" [7] [8].

Olson and Morton [11] [12] [13] found "*Over* 1 million ha *of agricultural bottomlands in Missouri and Arkansas were protected by the hundreds of kilometers of levees on the west side of the Mississippi River below New Madrid, Missouri, and west of the Floodway setback levee. These levees did not fail before, during, or after the use of the Floodway, and the* 2011 *agricultural production from this region was maintained. There could be a permanent loss of some agricultural production on two hundred hectares of land due to large deep gullies* (**Figure 11**), *on those parcels adjacent to the blown levees that are covered with a thick sand deposit, and on farmland that is now in the new crater lakes. Reclamation efforts by the USACE included the removal of the thick sand deposits, and the sand was used to patch the frontline and fuse plug levees between Birds Point, Missouri, and New Madrid, Missouri, or to partially fill in the crater lakes and adjacent gullies. Filled crater lakes at Birds Point have been covered with topsoil trucked in from outside the Floodway. The earthen levee was initially rebuilt to* 15.6 m (*fuse plug was previously at* 18.4 m *and frontline levee at* 19.1 m), *but after input from the local farmers and additional federal funding, the rebuilt levee was raised to* 16.8 m" [11] [12] [13].

Some of the road and drainage ditches which were filled with sediment were cleaned out by excavators by October of 2011 and proper drainage was restored to parts of the area. Other areas took another year for the drainage to be restored. However, the unanticipated fields with deep large gullies were difficult to repair (**Figure 12**). It was rather difficult to regrade and reshape these gullies in isolated cultivated fields on ridges or second-bottom soils. These fields of gullies caused the permanent loss of agricultural land. Even after reclamation of the fields of gullies, these soils had lower productivity. In many cases, the alluvial parent material became the land surface with less soil aggregation, less soil organic carbon, and more slope. The reclamation effort restored some of the permanently lost cropland in sand delta and crater lakes and/or created wildlife habitat and additional wetlands adjacent to the patched levees.

2.1.5. Len Small Natural Levee Breach During a Major Flooding Event

Olson and Morton [12] determined "*Agriculture, the dominant land use of the Mississippi River Basin for more than* 200 years, *has substantively altered the hydrologic cycle and energy budget of the region. Extensive systems of USACE and private levees from the Upper Mississippi River near Cape Girardeau, Missouri, southward confine the river and protect low-lying agricultural lands, rural towns, and public conservation areas from flooding. The Flood of* 2011 *severely tested these systems of levees, challenging public officials and landowners to make difficult decisions, and led to extensive damage to crops, soils, buildings, and homes. One of these critical levees* (**Figure 13**), *the Len Small in Illinois, failed, creating a* 1,500 *m breach* (**Figure 14**) *where fast-moving water scoured farmland, deposited sediment, and created gullies and a crater lake. The Len Small levee, built by the Levee and Drainage District on the southern Illinois border near Cairo to protect private and public lands from* 20*-year floods, is located between mile marker* 21 *and mile marker* 36 (**Figure 13**)*. It connects to Fayville levee that extends to Mississippi River mile marker* 39, *giving them a combined length of* 34 km *protecting* 24,000 ha *of farmland and public land, including the Horseshoe Lake Conservation area. The repair of the breached levee, crater lake, gullies, and sand deltas began in October of* 2011 *and continued for one year*" [12].

Figure 12. May of 2011 aerial view of O'Bryan ridge gully fields.

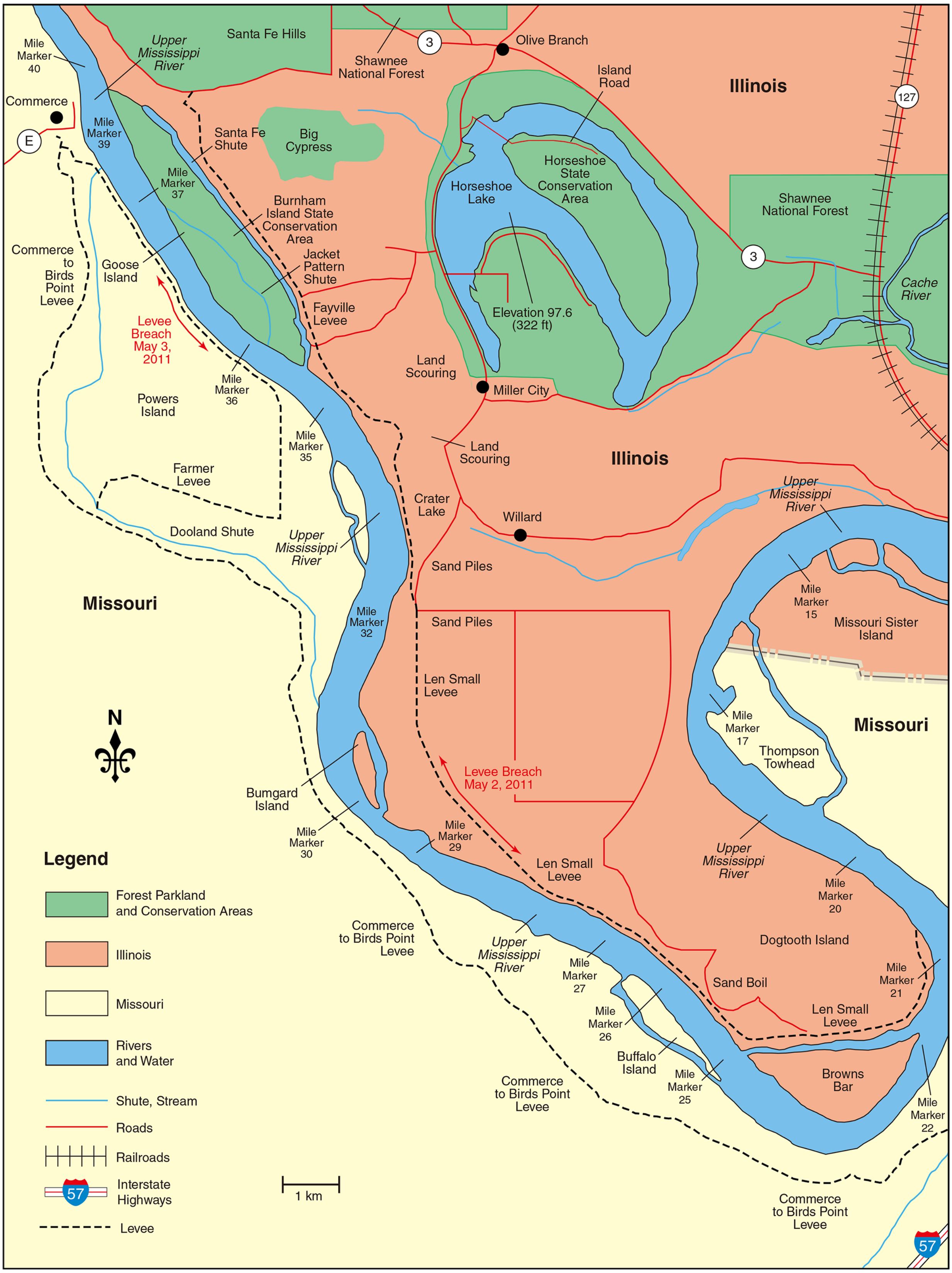

Figure 13. Alexander County, Illinois including the Len small levee and the northern part of the Commerce to Birds Point levee, Missouri areas.

Figure 14. Land scoring of the bottomland located below the O'Bryan Ridge gully fields.

2.1.6. Damages and Environmental Consequences of Man-Induced Levee Breaches in the United States

Olson and Morton found [11] [13] "*During the spring* 2011 *flooding along the Mississippi River, the strong current and sweep of water through the Birds Point, Missouri, levee breach in May of* 2011 *created a hundred hectares of deep gullies* (**Figure 12**)*; scoured hundreds of hectares of land; eroded tons of soil; filled ditches with sediment which blocked drainage; created sand deltas; and damaged irrigation equipment, farm buildings, and homes. Reclamation and restoration of these agricultural lands following the USACE opening of the New Madrid Floodway to relieve flood pressure on the levee system from the Mississippi River* [7] [8] *has been time-consuming and costly to individual landowners and public tax dollars. While levees were rebuilt, ditches cleared of sediment, and many lands in the floodway were restored by November of* 2012, *soil productivity and growing conditions continue to challenge the farmers of this historically highly productive region. The USACE decision to blow up Birds Point levee along the Lower Mississippi River and flood agricultural lands in the New Madrid Floodway* (*Missouri*) (**Figure 8**) *was difficult, with substantive legal challenges as well as social and political trade-offs between human life and property in urban and rural areas. The induced breach and flooding of* 53,824 ha *of Missouri farmland resulted in partial* 2011 *crop loss and permanent soil damage because of land scouring, gully fields* (**Figure 15**), *and crater lake areas* [7] [8]*. The opening of the floodway resulted in a* 3.0 *to* 3.6 m *wall of floodwater pouring through the* 1.8 km *hole in the breached levee and into the floodway with an average width of* 8 km, *which dropped the initial water depth by one fourth or to* 0.8 *to* 0.9 m *as it raced* 51 km *to the southwest toward New Madrid, Missouri. The fuse plug near New Madrid was blown up on May* 3, 2011, *to accelerate the return of the floodwater back into the Lower Mississippi River. The* *frontline levee near Big Oak Tree State Park was opened with trinitrotoluene* (*TNT*) *on May* 5, 2011 (**Figure 11**). *There was severe damage to most of the* 200 *building structures, including* 75 *homes, which were exposed to flowing floodwater. These buildings were damaged when they were partially submerged in* 1.8 *to* 3 m *of temporarily stored floodwater*" [11] [13].

2.1.7. Crop and Soil Productivity Loss

Olson *et al.* [14] found "*Flooding of agricultural lands after a natural or human-induced levee breach can have large and persistent effects on soils, crop productivity, and water quality, with negative economic, social, and ecological consequences. Many US water management strategies associated with levee-protected agricultural systems are dominated by policies that focus on engineered solutions designed to minimize short-term risk of flooding and breaching while overlooking resilience of the agroecosystem* [14]. *A federal damage assessment of the effects of levee breaches and flooding on public and agricultural lands is needed each time a levee fails. Most federal damage assessments only include the levee itself and the adjacent crater lakes, gullies, and sand deltaic deposits but not the remaining flooded areas. Land scouring, sediment deposition in drainage and road ditches, and soil productivity loss are the most severe damages to soils on agricultural lands. Levee breaches on the Mississippi River in the US interior have occurred since the Great Flood of* 1927 [15]. *The Flood of* 2011 [16] *on the Mississippi River well illustrates the impacts of flooding and levee breaching on agricultural soil conditions and productivity.*"

"*Levee breaches on the Mississippi River in the US interior have occurred since the Great Flood of* 1927 [16]. *The Flood of* 2011 [17] *on the Mississippi River well illustrates the impacts of flooding and levee breaching on agricultural soil conditions and productivity. The area of study for this paper is a* 78-ha *field on O'Bryan Ridge* (35˚51'09"N, 89˚11'03"W) *owned by Levee District Number* 3 (**Figure 12**) *that was impacted when the US Army Corps of Engineers* (*USACE*) *opened the New Madrid Floodway in Missouri by inducing a breach in the Birds Point fuse plug levee on May* 2, 2011 (**Figure 15**). *An unintended conversion of agricultural land to wetlands and ponds occurred within the land-scoured bottomlands* (**Figure 7**) (**Figure 14**) *in the O'Bryan Ridge field. These gully lands have since been partially regraded and reshaped to return the agricultural land to production. The dramatic changes in land use from levee breaching demonstrate the need for a land scouring and deposition survey* (**Figure 16**) (**Figure 17**), *an updated soil survey, and a soil and water conservation plan to reduce further soil loss and gully formation on reclaimed lands. An updated soil survey map with eroded and deposition phases of previously existing soils and new soil series can be used to estimate and compare the crop yields and production levels before levee breaching and after gully field creation and to guide the periodic reshaping and restoration of the gully fields. Further, gully fields within the New Madrid Floodway are likely to remain vulnerable to the next induced levee breach and subsequent flooding if a revised plan to protect the area is not developed*" [14].

Figure 15. Gullies and channels were created from May 16, 2011. The main channel and attached gullies were 4 m deep and removed cropland from production.

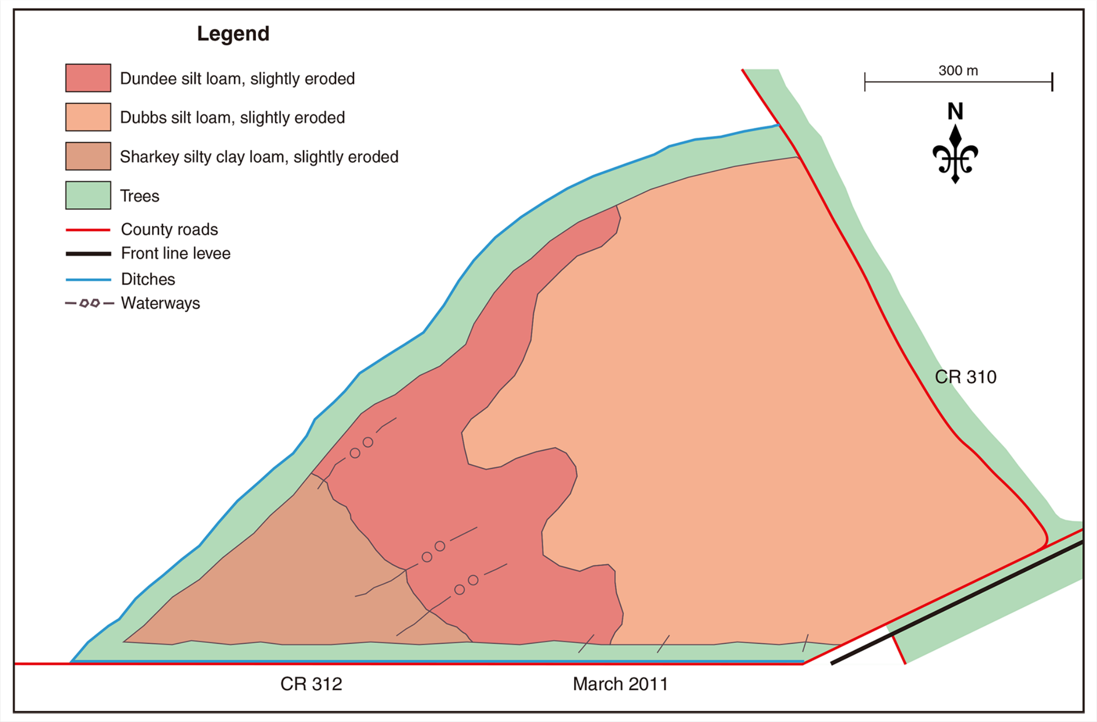

Figure 16. March of 2011 soils prior to levee breaching the floodway on O'Bryan Ridge. Cultivated Dubbs and Dundee soils form a natural levee to the east of the Sharkey bottomlands.

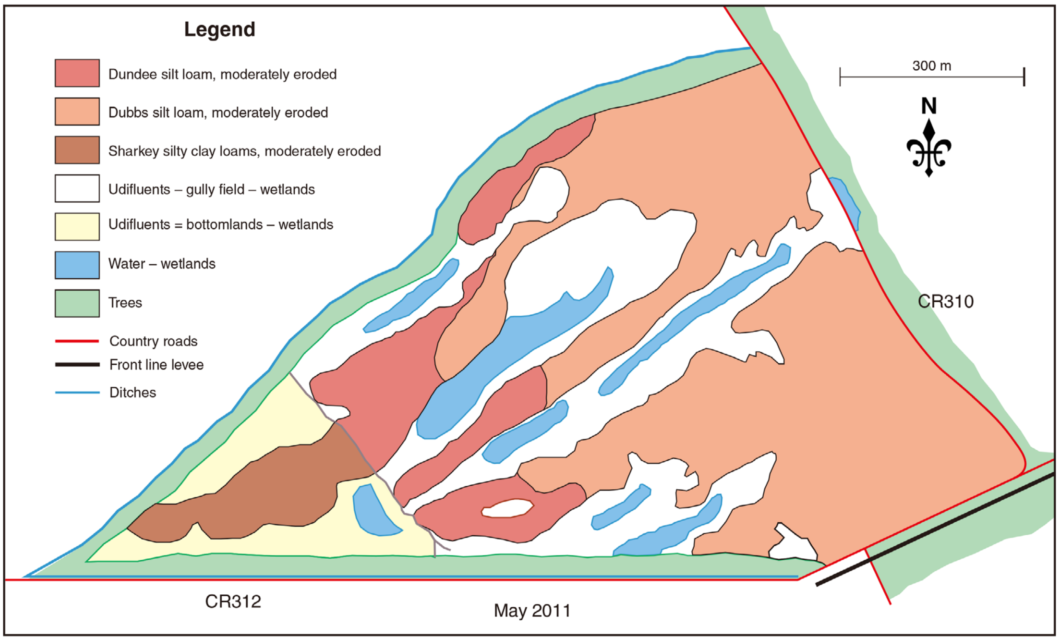

Figure 17. May of 2011 soil eroded phases of O'Bryan Ridge show soil loss and degradation with the creation of gully fields during the floodway use and flooding.

2.1.8. Proposed Redesign of the New Madrid Floodway

The year 2011 had 14 flooding events in the United States causing losses of more than one billion dollars each. The southeast Missouri region adjacent to the Lower Mississippi River illustrated the local impacts on agriculture and human settlements. Olson and Morton [7] [8] found that "*When early snow melts and record rainfall over the Ohio River Valley and lands in the Lower Mississippi River result in saturated soils, extreme flooding, and damage to crop production and community infrastructure. The May* 2011 *deliberate breaching of the levees in the New Madrid Floodway, Missouri, was a planned adaptation response to exceptional flooding conditions with the goal of reducing excess river pressure and preventing levee failures along the Ohio and Mississippi rivers* [17]. *Climate scientists observe that* 2011 *was not unique, finding that the last decade was likely the warmest globally for at least a millennium, triggering a period of precipitation and heat wave extremes. As long-term weather patterns become more variable and unpredictable, there is much that can be learned from reevaluating past adaptation strategies and the exploration of new alternatives*" [7] [8].

2.2. Case Study 2: The 1986 Chernobyl Explosion and 2023 Man Induced Kakhovka Dam Breach on the Dnieper River

Appearance of the Artificial 137Cs Isotope in the Soil, Water, and Sediment

After the Chernobyl explosion in Ukraine a radiation cloud (Figure 18) drifted 800 km to the northeast and over Soviet Union (Figure 5). When it rained near the city of Tula, south of Moscow, the 137Cs isotope levels in the soil were increased by 10-fold [18] [19]. Since the mid-20th century, the presence of the artificial 137Cs

Figure 18. Smoke from Chernobyl number 4 reactor burning. Aerial view. Photo Credit: Wikipedia.

isotope in the natural environment is related to nuclear accidents and nuclear tests in the atmosphere. After the Chernobyl accident in 1986, the accelerated development in Russia and adjacent countries occurred. Since most of the Chernobyl derived radioactive materials were washed down with rain, there is significant spatial variability of the Chernobyl-derived cesium-137 fallout onto vast areas in central Soviet Union [20] [21] [22][23] [24]. Dry deposition was more significant in the vicinity of the reactor, for relatively large/heavy aerosols and a relatively short period after the accident.

Ritchie and McHenry [25], using 137Cs isotope, identified soil loss and deposition. Cesium-137 was not present in soils prior to the atmospheric detonation of fissionable weapons. This occurred mostly in the late 1950s and early 1960s in the US, the time frame for 137Cs as a stratigraphic marker. Its behavior in soils is largely controlled by sorption processes on the surface of fine particles and their migration, due to soil erosion [26] [27]. Gennadiyev *et al.* [18] "*compared the radio-cesium and the technogenic magnetic tracer methods in the slightly eroded chernozems of Molochnye Dvory region in Russia which is in the southern Tula oblast. This area was affected by the Chernobyl accident in* 1986 *and the conventionally single fallout of cesium*-137 *on vast areas of Soviet Union. The two-component markers used differ not only in their origin and age but also in their forms of occurrence in the soils. The initial migration capacity of cesium*-137 *was higher than that of magnetic spheres, which is explained by the partial translocation of cesium in the ionic form and its predominant sorption by colloidal particles, which the observed magnetic spheres are larger in size* (*from* 1 *to* 25 μm)*. The loss of cesium*-137 *always exceeded the loss in magnetic spheres. Melin et al. [28], Shcheglov et al. [29]* [30] *showed the forest can have* *higher cesium*-137 *levels than cultivated fields because of tree intercepts. Du and Walling* (*in* 2011) [31] *used cesium*-137 *measurements to investigate the influence of erosion and soil redistribution of soil properties*" [18].

The hydroelectric power stations are Kyiv Hydroelectric Station built near Kyiv in 1964 (**Figure 18**), the Kaniv Hydroelectric Station built in Kaniv in 1975, Kremenchug Hydroelectric Station in Kremenchug in 1960, Middle Dnieper Hydroelectric Power Plant built near in Kamianske in 1964. The Kakhovka Hydroelectric Station built, between 1950 and 1959, near Kakhovka was destroyed in 2023 during the Russian-Ukraine conflict. There are six sets of dams and hydroelectric stations, from the mouth of the Pripyat River to the Kakhovka Hydroelectric Station, which produce 10% of Ukraine's electricity [5]. The Kakhovka dam (**Figure 19**) was destroyed on 6 June 2023 during the Russian invasion of Ukraine [32], with the subsequent drying up of the Kakhovka Reservoir (**Figure 20**) revealing the original course of the river in the area and disconnecting four canal networks [33]. The first dam, the Dnieper Hydroelectric Station near Zaporizhzhia, was constructed between 1927 and 1932 with an output of 558 MW [34]. It was destroyed during World War II, but was rebuilt in 1948 with an output of 750 MW.

Figure 19. Destroyed Dnieper River dam. New York Times. Photo Credit: Nicole Tung.

Figure 20. Dnieper reservoir bed after water level dropped. Photo Credit: AP.

Kakhovka Dam on the Dnieper River was destroyed on 6 June 2023 during the Russian-Ukraine conflict [33]. The dam destruction caused widespread flooding which affected settlements and farmland across the Dnieper watershed. Since the dam collapse (**Figure 18**), satellite images show water levels in both the reservoir and canals it feeds have continued to drop. The canals are the source of drinking water for 700,000 people living in southern Ukraine and irrigation for vast areas of farmland. Four canal networks have become disconnected from the reservoir. The water loss from the canals adversely affected food production in the region. Before the war, about 5840 sq km of cropland on both sides of the Dnieper River could potentially be serviced by the canals. More than half the area was reliant on irrigation systems [33]. These areas yielded about two million tons of grain and oil seeds in 2021, according to the Ukrainian government. The canals were used to irrigate summer-planted crops, such as corn, soybeans, and sunflowers. They were also used in the winter to irrigate winter wheat, vegetables, and fruit such as melons. The dam also reduced flooding downstream.

3. Results

The Dnieper is one of the major transboundary rivers (**Figure 1**) in Europe [2] [35] and was part of the Amber Road trade routes in antiquity. During the Ruin in the later 17th century, the area was contested between Russia and the Polish–Lithuanian Commonwealth. The river became noted for its major hydroelectric dams and large reservoirs during the Soviet period. The 1986 Chernobyl disaster (**Figure 21**) occurred on a tributary of the Dnieper, the Pripyat River, just upstream from its confluence with the Dnieper. The Dnieper is an important navigable waterway for the economy of Ukraine. The river is connected by the Dnieper–Bug Canal to other waterways in Europe. Segments of the river are part of the defensive lines, during the 2022 Russian invasion of Ukraine, between territory controlled by Russians and Ukrainians [36] [37] [38].

The Dnieper Rapids were part of the trade route used by the Greeks and Varangians. The route was probably most likely established in the late eighth and early ninth centuries and gained significant importance in the tenth and eleventh centuries. On the Dnieper the Varangians had to portage their ships round seven rapids. Along this middle flow of the Dnieper, there were nine major rapids and about 30 to 40 smaller rapids, and approximately 60 islands and islets. After the Dnieper hydroelectric station was built in 1932, they were inundated by Dnieper Reservoir (**Figure 22**) (**Figure 23**) (**Figure 24**).

This encouraged the digging of connecting water routes from the Dnieper to neighboring rivers in ancient times. At the end of the 18th century and the beginning of the 19th, the Dneiper-Bug Canal, running by way of the Bug, Pripet, and Vistula rivers; the Dnieper was connected to the Baltic Sea by several canals: the Ahinski Canal by way of the Pripet and the Neman. These canals later became obsolete. The Dnieper-Kryvyi Rih Canal, the Dnieper-Donbas canal the Irasnoznamianka Irrigation system, the Kakhovka Canal, and the North Crimean Canal all connect to the Dnieper River.

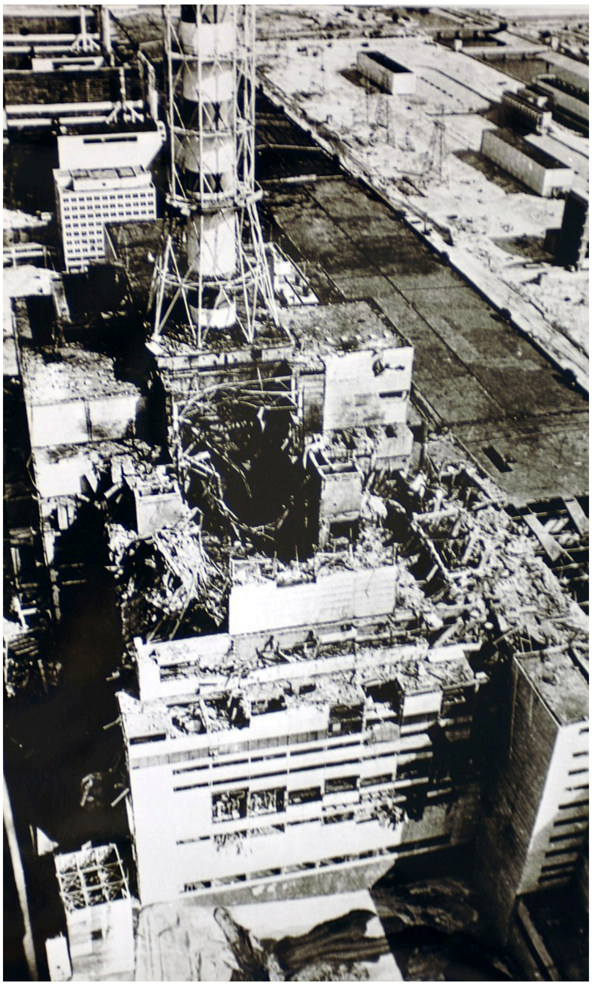

Figure 21. After Chernobyl nuclear plant explosion. Historical collection of Chernobyl accident. Photo Credit: Ukrainian Society for Friendship and Cultural Relations with Foreign Countries.

Figure 22. Bridge over the Dnieper River in Kiev, Ukraine. Photo Credit: Petar Milosevic.

Figure 23. Dnieper Reservoir. Photo Credit: Encyclopedia Britannica.

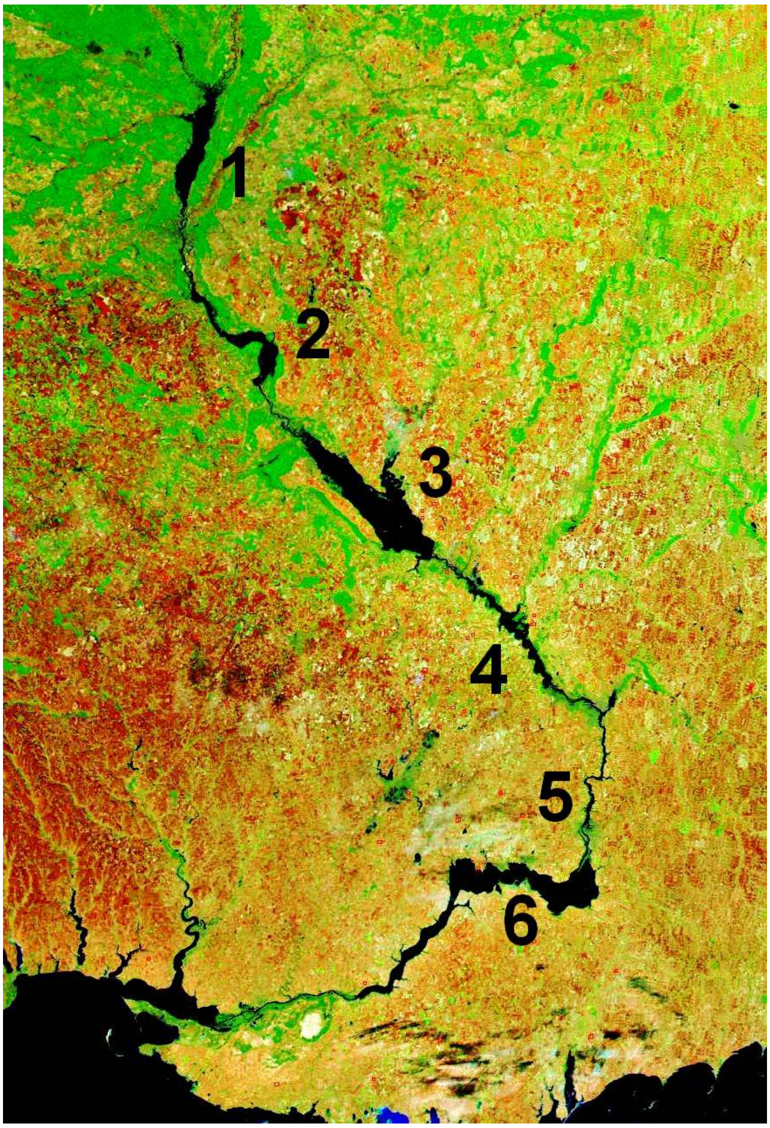

Figure 24. Satellite image of Dnieper River. Photo Credit: Encyclopedia Britannica.

3.1. Navigation

Almost 2000 km of the river is navigable [5]. The Dnieper is important for transportation in the economy of Ukraine. The reservoirs on Dnieper have large ship locks, allowing vessels of up to 270 m by 18 m access as far as the port of Kiev, and thus is an important transportation corridor. The river is used by passenger vessels as well. Inland cruises on the rivers Danube [39] and Dnieper have had a growing market in recent decades.

The Dnieper receives the water from the Pripyat River located upstream from Kiev (**Figure 1**). This navigable river connects to the Dnieper-Bug canal and link with the Bug River. A weir without any ship lock near the town of Brest, Belarus, has interrupted this international waterway a connection with the Western European waterways. Poor political relations between Western Europe and Belarus means there is little likelihood of reopening this waterway soon [40]. River navigation is interrupted each year by severe winter storms freezing.

3.2. The Chernobyl Disaster: What Happened? And What Was the Long-Term Environmental Impact

Blakemore [41] reported "*that an accident at a nuclear power plant in Ukraine shocked the world and permanently altered a region. On April* 25 *and* 26, 1986, *the worst nuclear accident in history unfolded in what is now northern Ukraine as a reactor at a nuclear power plant exploded* (**Figure 24**) *and burned. Cloaked in secrecy*, *the incident was a watershed moment in both the Cold War and the history of nuclear power. More than* 30 years *later*, *scientists estimate the zone around the former plant will not be habitable for up to* 20,000 years. *The disaster took place near the city of Chernobyl in the former USSR*, *which invested heavily in nuclear power after World War II. Starting in* 1977, *Soviet scientists installed four RBMK nuclear reactors at the power plant*, *which is located just south of what is now Ukraine's border with Belarus*" [41].

"*On April* 25, 1986, *routine maintenance was scheduled at V.I. Lenin Nuclear Power Station's fourth reactor* (**Figure 25**), *and workers planned to use the downtime to test whether the reactor could still be cooled if the plant lost power. During the test*, *however*, *workers violated safety protocols and power surged inside the plant. Despite attempts to shut down the reactor entirely*, *another power surge caused a chain reaction of explosions inside. Finally*, *the nuclear core itself was exposed*, *spewing radioactive material into the atmosphere. Firefighters attempted to put out a series of blazes at the plant, and eventually, helicopters dumped sand and other materials to squelch the fires and contain the contamination. Despite the death of two people in the explosions*, *the hospitalization of workers and firefighters*, *and the danger from fallout and fire*, *no one in the surrounding areas—including the nearby city of Pripyat*, *which was built in the* 1970s *to house workers at the plant—was not evacuated until about* 36 *hours after the disaster began*" [41].

Figure 25. Chernobyl nuclear plant. Photo Credit: Pawel Szubert.

3.3. Agricultural and Environmental Impacts of Chernobyl Explosion

All the world's soils used for agriculture contain radionuclides. Typical soils contain 300 kBq/m^3 of 40K to a depth of 20 cm. Radionuclide and other are taken up by crops and transferred to food, leading to concentrations in food and feed of between 50 and 150 Bq/kg. Ingestion of radionuclides in food is one pathway that contributes to human exposure from man-made and natural sources which can lead to internal retention [42]. Excessive contamination of agricultural land, such as a severe accident, such as Chernobyl, can lead to unacceptable levels of radionuclides in food.

Radionuclide contaminants of most significance in agriculture are those that are easily uptaken by crops, have relatively long radiological half-lives and have higher rates of transfer to animal products, such as meat and milk. Ecological pathways leading to crop contamination and the radioecological behavior of radionuclides are complex. The behavior is affected by the chemical and physical properties of the radionuclides but also by the cropping system, including tillage, soil type, climate, season, and the biological half-life within animals. The major radionuclides of concern in agriculture following a large reactor accident, such as Chernobyl, are 137Cs, 131I, 134Cs, and 90Sr [42]. In temperate regions, the major source of contamination is the direct deposition of plants. While cesium isotopes and 90Sr are relatively immobile in soil, direct deposition on plants is often more important than uptake via roots.

Soil type, and especially clay mineral and organic matter content, tillage practice and climate all can affect movement to the groundwater as well as uptake by the plants. Since cesium and strontium share the same uptake mechanisms as potassium and calcium, the uptake depends on the availability of these elements.

A high level of potassium fertilization can reduce cesium uptake by plants and liming can reduce strontium uptake by the crops.

The releases from Chernobyl contaminated 125,000 km^2 of land in Russia, Belarus, and Ukraine. Radio-cesium levels greater than 37 kBq/m^2 and radio-strontium greater than 10 kBq/m2 occurred on 30,000 km^2. Approximately 52,000 km^2 of agricultural land were contaminated. The remainder of the contaminated land was in forests, urban centers, and water bodies. The downward leaching of cesium in soil is generally slow, especially in forests and peaty soils. The leaching of cesium into the water table is affected by rainfall, pH, soil type and tillage. The radionuclides are generally attached to clay particles with a matrix of uranium dioxide, graphite, iron-ceramic alloys, silicate-rate earth, and silicate combinations [42].

The rate of movement of radionuclides in the soil depends on both soil properties and the chemical breakdown of these complexes by oxidation which releases more mobile forms. Most of the fission products are in the humic complexes. The radionuclides in the 30-km exclusion zone have declined due to natural processes and because of some decontamination measures.

The 137Cs activity concentration, in 1991, ranged from 25 to 1000 kBq/m^3 in the 0 - 5 cm soil layer and higher in pastures than in cultivated fields. Between 60% to 95% of all 137Cs were found to be strongly bound to particles in all soils. Ordinary plowing disperses the radionuclides more evenly in the tillage zone. This reduces the concentration in the upper 5 cm and reduces crop root uptake. When contaminated soil is removed, as part of a decontamination strategy, the quality of soil contaminated is increased significantly.

3.4. Agriculture

Countermeasures designed to reduce human exposure included cessation of fieldwork, less consumption of fresh vegetables, reduced pasturing of animals and poultry, and introduction of uncontaminated forages. Unfortunately, these measures were not introduced immediately which increased the contamination doses to humans in Ukraine.

In Ukraine, initially over 15,000 cows were slaughtered to reduce the contamination in the food chain when clean fodder could have reduced the risk. Other countermeasures that did help included the use of potassium fertilizers which decreased the uptake of radio-cesium by a factor ranging from 2 to 14 which also increased the crop yields [42]. In some soils, lime in combination with manure and mineral fertilizers can reduce the accumulation of radio-cesium in legumes and cereals by a factor of up to 30. In peaty soils, mineral soil applications can reduce the transfer of radio-cesium to plants by adhesion to the soil particles. The risk of radio-cesium to the food supply can be reduced by feeding cattle uncontaminated forages for ten weeks prior to slaughter. A government policy of promoting critical food production to the less contaminated areas in Ukraine also reduced the risk to the food supply.

3.5. Forests

Forests are diverse ecosystems where flora and fauna depend on each other as well as soil characteristics, topography, and climate. Forest are places for recreation, work, and a source of food. Wild game, berries and mushrooms are a supplemental source of food for the inhabitants of contaminated regions and timber products are important to the livelihood of the local population.

Radio-nuclide deposition is often greater in the forest than in agricultural areas due to the high filtering characteristics of trees [42]. Forest ecological pathways often have enhanced retention of contaminating radio-nuclides. The organic-rich forest floor soils increase the soil-to-plant transfer of radionuclides. Mosses, lichens, and mushrooms often exhibit high concentrations of radionuclides. The transfer of radionuclides to wild game in the forest creates a significant risk for humans dependent upon the game as a food source.

Forest workers in Russia were found to have received three times more radionuclides, in 1990, than others living in the same area. Forest-based industries, such as pulp production, often recycle chemicals that have been shown to be a potential radiation protection problem because of radionuclides in liquors, ashes, and sludges. Harvesting trees for pulp production is a viable strategy for decontaminating forests. Other strategies for combating forest contamination include the prevention of forest fires and restricted access. Another strategy is to remove and bury contaminated trees and soils which can reduce the contamination factor by 10. Changes in forest management and use can reduce the radiation dose. Prohibitions and/or restrictions of food collection and control of hunting can protect those who consume large quantities of forest game and food products. Dust suppression measures, such as re-forestation and sowing of grasses, undertaken on a wide scale can reduce the spread of existing soil contamination [42].

4. Discussion

4.1. Water Bodies

After an accident, such as Chernobyl, radionuclides contained bodies of water via direct deposition from the air, discharge as effluent or indirectly from catchment basin washout. When radionuclides contaminate large bodies of water, they are quickly dispersed and accumulate in water bottom sediments, aquatic plants, benthos, and bottom-feeding fish. The main pathways to humans are through contamination of drinking water, from use of water for irrigation, and consumption of contaminated fish. Contaminating radionuclides tend to disappear from water rather quickly. Human exposure is only likely during the initial deposition phase and later when the catchment basin washouts.

4.2. River Ecosystems

Radioactive contamination of river ecosystems was noted soon after the Chernobyl explosion. The total radioactivity of water in the rivers in April and May of 1986 was 10 kBq/L in the adjacent Pripyat River, 5 kBq/L in the Uzh River and 4 kBq/L in the Dnieper River. Short-term radionuclides, such as 131I, were the main contributors [42]. The contamination of water, sediments, algae, molluscs, and fish fell significantly as the river ecosystem drained into Kiev, Kanev, and Kremenchug reservoirs.

By 1989, the content of 137Cs in the water of the Kiev reservoir was 0.4 Bq/L, in the Kanev reservoir 0.2 Bq/L and in the Kremenchug reservoir 0.05 Bq/L. Similarly, the 137s content of Bream fish fell by a factor of 10 in the Dnieper between the Kiev and Kanev reservoirs and by a factor of two in the Dnieper between the Kanev and Kremenchug reservoirs (10 Bq/kg). During the last 3 decades, contamination of the water system has not posed a public health problem [42]. However, monitoring will need to continue to ensure that the catchment area washout, which contains a large quantity of stored radioactive waste, will not contaminate Kiev drinking water. The presence and breach-induced redistribution of Chernobyl-derived nuclides is an additional condition not present at the New Madrid man-induced levee breach. The assessment survey must be delayed until after the Russia-Ukraine conflict is over.

A hydrogeological study of the groundwater contamination in the 30-km exclusion zone has found 90Sr to be the most critical radionuclide which could continue to contaminate drinking water to above acceptable limits for another 70 years. After the breach, the bottom reservoir sediments with nuclides, dried and were blown onto the surrounding uplands.

4.3. Man Induced Dam and Levee Breaches

The primary objectives were to assess lessons learned from man-induced levee breaches in the United States to mitigated and restore environmental damages from man-induced dam breach on the Dneiper River land restore Ukraine's lifeline. Nowadays the Dnieper River suffers from pollution as a result of anthropogenic influence. The Dnieper is susceptible to leakage of its radioactive waste and is close to the Prydniprovsky Chemical Plant radioactive dumps. The Chernobyl Nuclear Power Station which is located next to the mouth of the Pripet (Pripyat) River is close to Dnieper River. On April 25 and 26, 1986, the worst nuclear accident in history unfolded in northern Ukraine as a reactor at a nuclear power plant exploded and burned.

The decision to blow up the Birds Point frontline levees and fuse plugs had significant consequences for rural Missouri landowners, residents, and farmers in the New Madrid Floodway. The impact of the floodwaters on the Floodway appears to have been greater than anticipated in part because of the delay in opening the Floodway due to legal action. When the USACE was given permission, by the US Supreme Court, to open the Floodway, the Mississippi River was 1.2 m higher than planned for, and the initial additional force and depth of floodwater caused more damage to buildings and more deep land scouring than was previously predicted. The loss of the 2011 wheat crop production was reduced by 8094 to 12,146 ha because of poorly drained clayey soils that were not replanted in 2011. Most of the farmland in Floodway dried out sufficiently to permit fall planting of wheat. It appears that all the Floodway were sufficiently dry by spring of 2012 to allow the planting of corn and soybeans. It is not clear how much of 2011 farm income replacement came will come from flood insurance since not all Floodway farmers had crop insurance.

Olson and Morton [8] determined "*Reclamation efforts by the USACE have removed much of the thick sand deposits, and the sand was used to patch the frontline and fuse plug levees between Birds Point, Missouri, and New Madrid, Missouri, or to partially fill in the crater lakes and adjacent gullies. Filled crater lakes at Birds Point have been covered with topsoil trucked in from outside the Floodway. The earthen levee was initially rebuilt to* 15.6 m, *fuse plug was previously at* 18.4 m, *and frontline levee at* 19.1 m, *but after input from the local farmers and additional federal funding the rebuilt levee was raised to* 16.8 m. *Most of the drainage and road ditches which were filled with sediment were cleaned out by excavators prior to spring of* 2012 *and proper drainage was restored. However, the unanticipated fields with large and deep gullies will not easily be repaired. It will be rather difficult to reshape and regrade these gullies in isolated cultivated fields on ridges or second-bottom soils. These fields of gullies could cause the permanent loss of agricultural land unless a federally funded land reclamation program is developed. Even if the fields of gullies are reclaimed, these soils are likely to have lower productivity. In many cases, the alluvial parent material will become the land surface and will have less soil aggregation, have less soil organic carbon, and be more sloping. The reclamation effort could restore some of the permanently lost cropland in crater lakes and sand delta and/or create additional wetlands and wildlife habitat adjacent to the patched levees*" [8].

Kakhovka Dam on the Dnieper River was constructed 1950s and destroyed on 6 June 2023 during the Russian-Ukraine conflict. The dam destruction caused widespread flooding which affected settlements and farmland across the Dnieper watershed. Since the dam collapse, satellite images show water levels in both the reservoir and canals it feeds have continued to drop. The canals are the source of drinking water for 700,000 people living in southern Ukraine. They also provided irrigation for vast areas of farmland. Four canal networks have become disconnected from the reservoir. The water loss from the canals adversely affected food production in the region.

5. Conclusions

The worst nuclear accident in history unfolded the Dnieper River watershed in northern Ukraine as a reactor at the Chernobyl nuclear power plant exploded and burned. After an accident, such as Chernobyl, radionuclides contained bodies of water via direct deposition from the air, discharge as effluent or indirectly from catchment basin washout. When radionuclides contaminate large bodies of water, they are quickly redistributed and tend to accumulate in water bottom sediments, benthos, aquatic plants, and bottom-feeding fish. The main pathways to humans are through contamination of drinking-water, from use of water for irrigation, and consumption of contaminated fish. Kakhovka Dam on the Dnieper River was destroyed during the Russian-Ukraine conflict and the dam needs to rebuild as soon as possible.

The Kakhovka Dam destruction caused widespread flooding which affected settlements and farmland across the Dnieper watershed. Four canal networks have become disconnected from the feeder reservoir. The canals were the source of drinking water for 700,000 people living in southern Ukraine. The Kakhovka canals also provided irrigation for vast areas of farmland. The water loss from the canals adversely affected food production in the region.

6. Recommendations

Lessons learned by the United States Army Corps of Engineers (USACE), after using TNT to blow-up the earthen Birds Point front line levee on the Mississippi River in May of 2011, can be applied to the man-induced 2023 Kakhovka Dam breach. The Birds Point-induced breaches and subsequent flooding of farmland resulted in the loss of the 2011 crops and damaged the future soil productivity. The strong current and sweep of the water through the three man-induced levee breaches on the New Madrid floodway levee created deep gullies, displaced tons of soil, and damaged irrigation equipment, farms, and homes.

Both a soil survey and an erosion and sediment survey need to be conducted as soon as possible after the flood water levels drop to determine the extent of the soil erosion and sediment deposition damage to the existing soils of the river landscape. The environmental damage to agricultural lands needs to be mitigated. The drainage ditches and canals need to be cleaned out and the waterways opened to drain the water remaining in the ponded areas. Any irrigation systems need to be restored as well as the canals which provide drinking water. Topsoil needs to be added to the eroded land surface and to fill in the gullies and to restore the long-term productivity of the soils.

Conflicts of Interest

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

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