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IAEA-TECDOC-1886

IAEA-TECDOC-1886

Environmental Impact Assessment of the Drawdown of the Chernobyl NPP Cooling Pond as a Basis for Its Decommissioning and Remediation

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ENVIRONMENTAL IMPACT ASSESSMENT OF THE DRAWDOWN OF THE CHERNOBYL NPP COOLING POND AS A BASIS FOR ITS DECOMMISSIONING AND REMEDIATION

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IAEA-TECDOC-1886

ENVIRONMENTAL IMPACT ASSESSMENT OF THE DRAWDOWN OF THE CHERNOBYL NPP COOLING POND AS A BASIS FOR ITS DECOMMISSIONING AND REMEDIATION

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2019

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Printed by the IAEA in Austria
October 2019

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Environmental impact assessment of the drawdown of the Chernobyl NPP cooling pond as a basis for its decommissioning and remediation / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2019. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1886 | Includes bibliographical references.
Identifiers: IAEAL 19-01271 | ISBN 978–92–0–161619–7 (paperback : alk. paper) | ISBN 978–92–0–161719–4 (pdf)
Subjects: LCSH: Chernobyl Nuclear Accident, Chornobylʹ, Ukraine, 1986 — Environmental aspects. | Reservoir drawdown. | Cooling ponds. | Environmental impact analysis.

FOREWORD

Many States experience problems with the decommissioning of nuclear installations and the remediation of radioactively contaminated sites. Under the terms of its Statute, the IAEA is authorized to foster the exchange of scientific and technical information on peaceful uses of atomic energy. In response to the needs of its Member States dealing with problems of radioactive contamination of the environment, IAEA efforts are directed at ensuring that environmental issues are given appropriate consideration, and relevant problems are addressed and managed in a safe, technically sound and efficient way.

One important mechanism for sharing experiences and promoting best practice in decommissioning and environmental remediation is to exchange information among specialists through publications. This publication presents technical and scientific information and data on the radiation monitoring, radioecological research, management and decommissioning of the cooling pond at the Chernobyl nuclear power plant, which was severely contaminated with radioactive material released from Unit 4 during the accident.

The IAEA provided assistance to the cooling pond decommissioning project in 2012–2013 through a sequence of expert missions, workshops and a number of modelling and risk assessment analyses supporting the feasibility study and the preparation of environmental impact assessments. This publication focuses on the assessment of radiological impacts resulting from the drawdown of the water level in the cooling pond as a basis for planning its decommissioning and remediation activities. This publication also summarizes the practical experience gained in the first few years of the cooling pond decommissioning project, which started in 2014 and is still ongoing.

Although specific to the cooling pond at the Chernobyl nuclear power plant, the findings, conclusions and recommendations presented by the international scientific community will be of benefit to all States. Many of the safety issues and challenges posed by the decommissioning of the cooling pond are similar to those encountered in the decommissioning and remediation of similar facilities and sites; and the lessons from the Chernobyl nuclear power plant can serve as a guide to decision makers.

The IAEA gratefully acknowledges the Ukrainian experts responsible for drafting and reviewing this publication and the contributions from the international scientific community. The IAEA officer responsible for this publication was H. Monken-Fernandes of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The cooling pond of the Chernobyl Nuclear Power Plant (ChNPP) represents an artificial reservoir, which was constructed on the floodplain of the Pripyat River to the southeast from the power plant. When ChNPP Units 3 and 4 where put into operation, the area of the pond constituted ~22km^2, and its volume was ~ 150×10^6 m^3. The operational water level in the pond was by 7 m higher than in the adjacent Pripyat River. The dam and sandy bottom of the pond was not isolated at time of construction by any low permeability lining. This engineering design resulted in large seepage losses from the pond of an order of ~100×10^6 m^3/year. The water level in the pond was maintained by constantly pumping water from the Pripyat River.

The cooling pond of was seriously contaminated in the course of the Chernobyl accident due to radioactive fallout on the water surface, and due to releases of highly contaminated water from the Unit 4 (water from the reactor emergency cooling system, water used for firefighting, etc.). With time, the main part of radioactive contaminants (^{137}Cs, ^{90}Sr, Pu and Am isotopes) have accumulated in the bottom sediments of the reservoir.

During the first decade following the Chernobyl accident releases of contaminated groundwater from the cooling pond represented one of major sources of contamination of the adjacent Pripyat River by ^{90}Sr, and a number of attempts has been maid (largely unsuccessful) to contain radioactivity within the pond. In later period, the radioactivity releases from the pond decreased in time due to natural attenuation process in the cooling pond surface water system. In addition, radiological impact assessment analyses has shown generally low radiological exposure doses related to groundwater pathway from the pond due to large dilution of radioactivity in the Pripyat-Dnieper River system. Therefore, groundwater remedial projects for the cooling pond were suspended.

With the closure of the ChNPP and shutting down of the last reactor Unit 3 in 2000, there was no need to maintain the cooling pond in its previous volume as a technological cooling water reservoir.

Since early 1990s, a series of international as well as Ukrainian national research project and remedial feasibility analyses were carried out in order to analyze various aspects of the cooling pond problem, and to develop the strategy and technical approaches for decommissioning and remediation of the cooling pond [1–8]. List (in table format) and summary description of main projects aimed at data collection and developing decommissioning and remedial strategies for the Chernobyl NPP cooling pond is provided in Appendix I.

Maintaining the water level in the pond was recognized as not a viable long-term management option, especially due to the need constantly replenish pond with water from Pripyat River by means of pumping station, and related high operation and maintenance cost. There was also a risk of cooling pond dam failure due to geotechnical stability problems. Thus, the drawdown of water level in the pond (in a “natural” or controlled mode) has been identified as an ultimate option for the Chernobyl pond decommissioning.

The predicted consequence of the water level drawdown in the pond is dewatering and exposure to atmosphere of highly contaminated bottom sediments. These dried up bottom sediments can represent a source of resuspension and atmospheric dispersion of radioactive aerosols. Therefore, the important subject of the decommissioning and remedial analyses of the cooling pond was risk assessment and development of approaches for managing of contaminated bottom sediments.

In 2013, the ChNPP (operator of the site) has contracted the Institute of Problems of Safety of NPPs (IPS NPP) affiliated to the Ukrainian National Academy of Sciences to prepare the feasibility study for decommissioning of the cooling pond, as a part of the comprehensive nuclear power plant decommissioning programme [8]. The decommissioning design project resulted in the official feasibility and EIA report for the decommissioning of the cooling pond, which was prepared in accordance with the relevant Ukrainian regulatory requirements. At preliminary stage, the radiological end-state criteria for the cooling pond decommissioning and environmental impact scenarios to be evaluated in EIA report were coordinated by the ChNPP with the regulatory authorities. The report was subject to official review by Ukrainian radiation safety regulatory authorities, and it was approved in 2014.

The feasibility study developed by IPS NPP [8] was based on the previous monitoring, modeling and remedial design analyses of the cooling pond listed above (see Appendix I). The project was carried out with the broad participation of the experts representing various Ukrainian research organizations and institutes of the Ukrainian Academy of Sciences. The IAEA provided assistance to the cooling pond decommissioning project through a sequence of expert missions, workshops and through directly funding of a number of modeling and risk assessment analyses supporting the feasibility study and EIA report preparation.

The cooling pond decommissioning started in 2014, when the pond pumping station was shut down, and water level in the pond starts to decline due to seepage and evaporation losses. Monitoring observations carried out since that time allow comparison of modeling predictions and actual dynamics of hydrological, radioecological and ecological parameters of the cooling pond in the course of water level drawdown.

The problems of the similar nature occurred at other nuclear facilities, for example at Par Pond at Savannah River Site [9], Karachay Lake at “Mayak” facility [10], at TOMSK-5 accident site in Russia [4] etc.

Therefore, it is anticipated that the experience of monitoring, radioecological research, as well as remedial and decommissioning analyses for the Chernobyl cooling pond can be of broad interest to the scientific and technical community, in particular for developing the ER&D designs for the similar radioactively contaminated facilities/sites and aquatic systems.

1.2. OBJECTIVE

The objective of this publication is to collate and disseminate the relevant technical and scientific information and data regarding the radiation monitoring, radio-ecological research and management of the Chernobyl nuclear power plant cooling pond. In particular, report focuses on the assessment of the environmental and radiological conditions after the pond drawdown, as a basis for justification of the decommissioning and remediation strategy for the pond.

Special attention is paid to the analyses of the need of remedial actions to reduce ongoing or potential doses to members of the public and staff of ChNPP due to radiological impacts resulting from the drawdown of water level in the pond. The relevant impacts analyzed in this report include atmospheric dispersion of the dried up radioactively contaminated bottom sediments, seepage of contaminated groundwater to Pripyat River, external exposure, and other impacts.

The report also aims at summarizing the practical experience of first several years of implementation of the cooling pond decommissioning project, which started in 2014 and continues until present time. In particular, report compares modelling predictions of the dynamics of the cooling pond drainage and related radiological and ecological impacts with the actually observed consequences of the drawdown of the water level in the cooling pond, and summarizes the lessons-learned.

1.3. SCOPE

The report reviews the available monitoring data, scientific and technical reports and publications on characterization and modeling studies carried out during the post-Chernobyl accident period with regard to the problem of radioactive contamination of the ChNPP, as well as data of previous assessments of the radiological impacts to humans and the environment associated with the decommissioning of the pond.

The subject of specific interest is use of risk assessment as a basis for justification of the approaches (strategy, technologies) for decommissioning of the pond, for planning of remedial actions to be implemented at the site, as well as practical experience in the implementation of the decommissioning programme for the Chernobyl cooling pond available at the time of preparation of this report.

1.4. STRUCTURE OF THE REPORT

Report consists of seven main sections, a number of appendices, and a list of references.

The section 1 (this section) describes problem background, objectives, scope and structure of the report.

Section 2 presents information on technical design and environmental conditions of the cooling pond.

Section 3 provides information on radioactive contamination of the cooling pond including main environmental media and compartments of the cooling pond such as bottom sediments, surface water system, groundwater system and aquatic biota. Data on contamination levels of surrounding territory and on adjacent radioactive waste storage sites are presented (i.e. on the “radiological context” of the cooling pond). Mechanisms of radioactive contamination of the Pripyat River due to water seepage from the cooling pond and history of related groundwater remedial measures are discussed.

Section 4 is devoted to presenting of the data and results of assessment of radiological and ecological impacts related to the water level drawdown in the cooling pond. Predicted rate of water level drawdown in the cooling pond and the end-state hydrogeological conditions are discussed among other subjects. Analyzed radiological impacts include atmospheric transport of radioactivity from the exposed bottom sediments and scenario of fire of contaminated vegetation growing on top of drained bottom sediments. Other exposure pathways include external exposure from the drained bottom sediments and groundwater transport of radionuclides to Pripyat River. Potential impacts of the water level drawdown on the cooling pond ecosystem (water quality, aquatic vegetation and habitat, etc.) and related “ecological” risks are also discussed.

Section 5 presents the decommissioning and remediation strategy for the cooling pond, which was developed by Ukrainian scientists and engineers based on results of radiological impact assessment analyses discussed in section 4. Separate paragraphs are focused on the end-state radiological criteria for the cooling pond, general sequence and timing of decommissioning activities and compliance monitoring programme. Special attention is paid to analysis of technological approaches for remediation of the contaminated bottom sediments of the cooling pond.

Section 6 is devoted to analyses of practical experience in decommissioning of the cooling pond in 2014–2017. *A priori* modeling predictions are compared to actual consequences of the cooling pond drainage, including time dynamics of relevant hydrologic and radiation parameters (e.g. water level drawdown rate in the pond, etc.). Lessons learned are presented, and outstanding issues are outlined.

Eventually, Section 7 summarizes main conclusions of the report.

A number of axillary supporting information and data is compiled in Appendices to the report.

2. TECHNICAL DESIGN AND ENVIRONMENTAL CONDITIONS

The main sources of information and data for this section are reports and publications [4, 5, 8]. In case other sources are used, these are explicitly referenced below.

2.1. DESCRIPTION OF THE COOLING POND HYDRO-ENGINEERING AND TECHNICAL DESIGN

2.1.1. General description and operation history of the cooling pond

The cooling pond of Chernobyl Nuclear Power Plant (ChNPP) was designed to provide cooling water to the heat exchanger equipment of the power plant, as well as to supply water for a number of other technological needs (e.g. to the spent nuclear fuel storage, the firefighting purposes, etc.).

The cooling pond represents an artificial reservoir, which was constructed on the floodplain of the Pripyat River to the southeast from the power plant. The perimeter of the cooling pond is formed either by the first terrace of Pripyat River overlying the floodplain or, for the most of its perimeter by the ~6 m in height dam constructed of local sandy soil (FIG. 1).

The cooling pond was constructed in 1976. Initially the cooling pond had a surface area of 12.7 km^2, and it provided cooling for the ChNPP Unit 1 (commissioned in 1977) and Unit 2 (commissioned in 1978) (FIG. 1).

The volume of pond was enlarged in 1981 by constructing a new segment of the dam encircling additional area of the Pripyat River floodplain. This was caused by the need to provide additional cooling capacity for ChNPP Units 3 (commissioned in 1983) and Unit 4 (commissioned in 1984). As a result the cooling pond reached its final dimensions with the surface area of 22.9 km^2. Some basic data on dimensions of the pond are listed in TABLE 1.

TABLE 1. TECHNICAL CHARACTERISTICS OF THE COOLING POND

Length, km	Mean width, km	“Normal operational water level” in the pond, m (above sea level, a.s.l).	Surface area at normal water level, km^2	Volume, million m^3	Average depth, m	Maximum depth, m
11.5	2.2	111.0	22.9	151	6.6	18.5

Information on the operation history of the cooling pond in relation to the operation of ChNPP is summarized in TABLE 2.

Once the last Unit 3 of ChNPP stopped functioning in December 2000, there was no further technological need to maintain the pond as a cooling facility of the power plant.

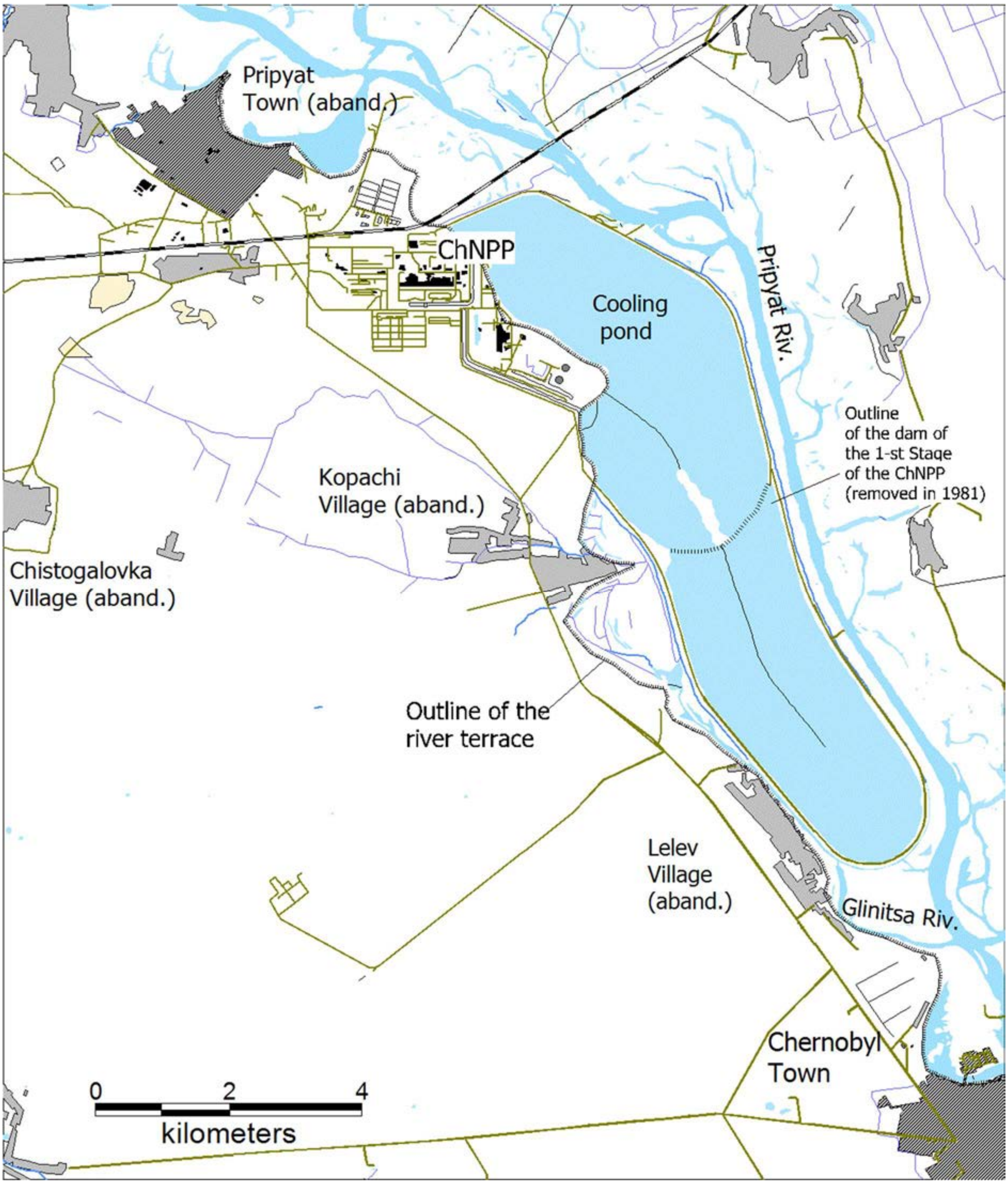


FIG. 1. Map showing location of the cooling pond relative to ChNPP.

TABLE 1. OPERATION HISTORY OF THE CHNPP COOLING POND

Date	Event
1976	Commissioning of the first section of the cooling pond (12.7 km^2) to provide cooling for the first stage of ChNPP (Units 1 and 2)
1981	Increasing of the cooling pond area (up to 22.9 km^2) to provide cooling of the second stage of ChNPP (Units 3 and 4)
26 April 1986	Chernobyl accident
11 October 1991	Following the fire in the turbine room, the Unit 2 of ChNPP is stopped
30 November 1996	Unit 1 of ChNPP was stopped
15 December 2000	The last functioning Unit 3 of ChNPP is stopped
2013	A smaller technological water supply reservoir for ChNPP is constructed by isolating a section of inflow and outflow channels of the cooling pond by cut-off dikes for replacement of the cooling pond (for firefighting and other technological needs)
May 2014	The pumping station replenishing cooling pond with Pripyat River water stopped to operate; cooling pond water level draw-down has begun

2.1.2. Hydro-technical design of the cooling pond

The water level in the pond during its exploitation period was maintained at 110.5–111.0 m a.s.l., which is about 7 m above the mean yearly water level in the adjacent Pripyat River, which is situated in the close vicinity of the pond. The strip of land between the dam of the cooling pond and Pripyat River is 200–400 m wide and ~ 11 km long (FIG. 2).

The water level in the pond was controlled by constantly pumping water from the Pripyat River to compensate for seepage losses and evaporation losses. The question of water balance of the cooling pond is discussed in more detail in the next section.

The pumping of water from Pripyat River was carried out by a pumping station equipped with 4 electricity pumps each with a production rate of 11400 m^3/hour. This pumping station is situated in the northeast corner of the pond (so called BNS-3 station; FIG. 2).

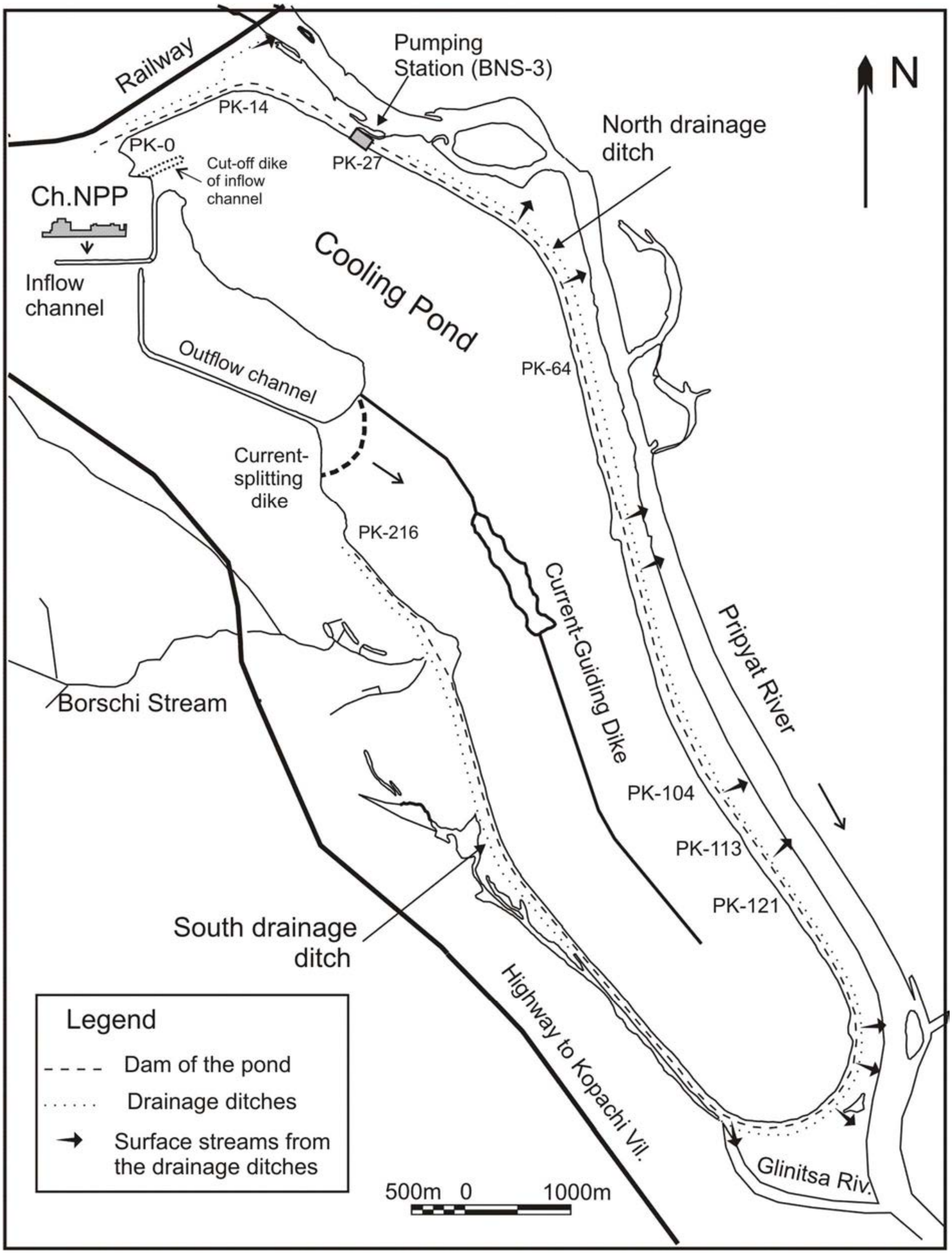


FIG. 2. Scheme illustrating the technical design of the cooling pond of ChNPP.

The dam of the cooling pond was built from local alluvial sands of the Pripyat River flood plain using a hydraulic fill method. The average height of the dam is ~ 6 m about the level of Pripyat River floodplain, while the width is 70 – 100 m. The crest of the dam has an elevation 112 m a.s.l. The inner (“wet”) slope of the dam (from the side of the pond) has the slant of 1:30–1:40; the outer slope has the slant of 1:3 and is reinforced by cobble backfilling. The dam has referenced coordinate marks (concrete posts) called “pickets” (PK) along its perimeter from PK–0 to PK–216 (FIG. 2 and FIG. 3).

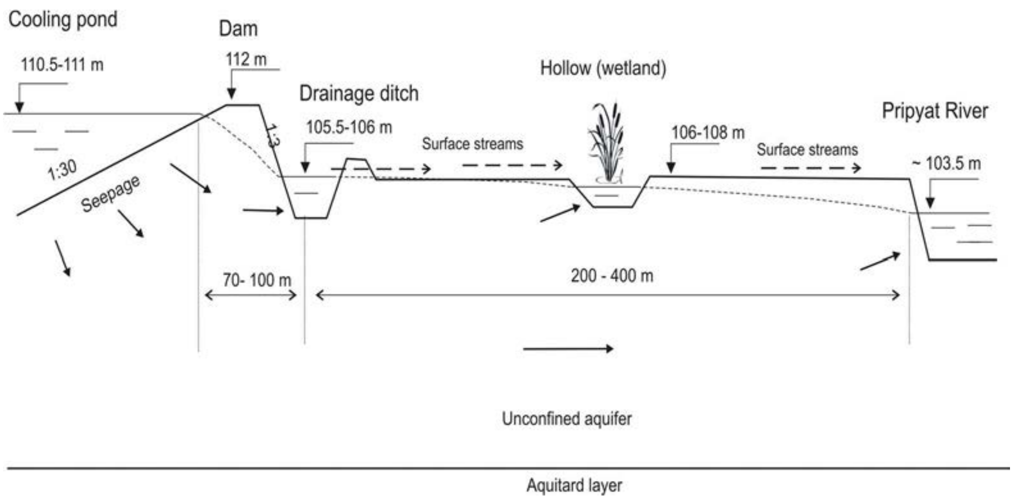


FIG. 3. Schematic cross-section of the dam of the cooling pond in the direction of Pripyat River (not to scale).

The dam and bottom of the pond was not isolated at time of construction by any low permeability lining. This design had led to high seepage from the pond towards Pripyat River, with yearly seepage loses estimated from ½ to 2/3 of cooling pond volume [11].

The drainage ditches were constructed at the base of the dam to collect and withdraw the seepage water from the pond. These ditches consist of two main segments: North Drainage Ditch and South Drainage Ditch (FIG. 2). The water level in ditches constituted 105– 106 m a.s.l, which was 1.5–2 m above the mean water level in Pripyat River. The drainage water from North Drainage Ditch discharged to Pripyat River through a dozen of surface streams. The drainage water from South Drainage ditch was discharged by natural flow to Glinitsa River (inlet) of Pripyat River. In between the North drainage ditch and Pripyat River a chain of small lakes (hollows) and wetlands was present, which collected water coming by surface run-off (streams) from drainage ditch as well as subsurface seepage from the pond (FIG. 3).

The dam of the cooling pond was equipped with the system of piezometer wells to control distribution of water pressure and thus technical state of the dam. In addition, special groundwater monitoring system was developed to monitor radionuclide migration in the subsurface from the cooling pond to Pripyat River. In particular, observation well profiles for monitoring radionuclide migration were installed at PK-14, PK-64, PK-113 and PK-121 of the dam of the cooling pond (FIG. 2). Groundwater monitoring data will be discussed and analyzed in more detail in section 3.4 of this report.

The cooling of water in the pond occurred due to convective heat exchange with the atmosphere. The cooling water was directed to the heat exchanger equipment of the power plant through the 1.5 km long inflow channel lined with concrete slabs. The heated water was released to the outflow channel consisting from the closed (subsurface) lined channel (1.15 km long) and open channel (2.4 km long). Both channels are lined with concrete slabs. Before entering the pond, the water passed a current-splitting dike representing a circular dike with openings for even distribution of the currents of outflowing heated water to the pond water surface. The further water circulation in the pond was controlled by a current – guiding dike located along the longitudinal axis of the pond (FIG. 2).

Following the Chernobyl accident, a special 500 m long "cutoff dike of the intake channel" was built near the mouse of the intake channel in the northern (most heavily contaminated) part of the pond to reduce inflow of the higher contaminated water to the technological cooling circuits of ChNPP (FIG. 2).

2.1.3. Concerns with regard to the geotechnical stability of the cooling pond dam

From the very beginning of exploitation in 1976, the segment of the cooling pond dam in the immediate vicinity of the pumping station suffered from suffosion process and development of the preferential high seepage zones. In particular, such channels of concentrated seepage have developed in the zone of contact between the concrete elements of the pumping station and surrounding soil material, such as the zone below the concrete base plate of the pumping station. The dam defects caused by suffosion were repaired on numerous occasions in 1981–2004 by backfilling suffosion voids with sand, cobble and injecting grout material. However, conclusion of the engineering expertise of dam stability carried out in 2004 stated that the implemented mitigation measures have potential for only delaying or lowering the intensity of hazardous suffusion process, and the discussed suffosion process represent an essential risk for the long-term stability of the dam [8].

In addition, a risk existed of the dam erosion by the adjacent Pripyat River. In consequence of high river flow events (i.e. high spring flood in spring 1999) significant erosion of the bank of Pripyat River in the vicinity of the cooling pond was observed with the estimated bank erosion rate of ~ 1 m/year [4].

After 2004 due to ChNPP budget difficulties the dam repair works were not conducted at a needed scale, which created a risk of development of accidental situation leading to the dam breach.

Therefore, geotechnical stability of the cooling pond dam was considered as a serious concern by cooling pond decommissioning and remedial analyses cited above, especially in the long-term (when dam maintenance will be suspended).

2.1.4. Water balance of the cooling pond

The question of the water balance of the cooling pond is important, as an accurate knowledge of water losses from the pond and their possible changes over time is a prerequisite for predicting the rate of water level drawdown in the pond in the process of cooling pond decommissioning.

The water losses from the cooling pond include two main components: evaporation loss and filtration (seepage) loss (FIG. 4).

When Units 1–3 of ChNPP still operated in 1989–91 the elevated temperature in the cooling pond caused increased evaporation rate from the water surface, which was estimated at Q_e=1300–1500 mm/year or (30–35)×10^6 m^3/year for the whole reservoir [11]. Once all units were shut down and the heat load from ChNPP disappeared, the net evaporation rate from the water of the pond decreased to about Q_e=200–300 mm/year (~ 4.4–6.6) ×10^6 m^3/year), which is a characteristic net evaporation rate for natural water bodies in the area [5].

The seepage losses from the pond are more difficult to estimate, as this parameter cannot be measured directly.

The water balance of the cooling pond was analyzed previously in several publications and reports [4, 11–13].

Below we present the most recent estimates of the cooling pond water balance (in particular with regard to seepage losses) based on purposeful experimental studies carried out in 2001 in the EC-funded project aimed cooling pond remedial analyses [5].

The water balance of the cooling pond can be described by the following equation [4, 11]:

$$Q_t = Q_e + Q_f,$$

where Q_t is net total rate of the water loss from the pond, Q_e is the net evaporation loss (i.e. difference between the net evaporation from pond surface and rainfall), and Q_f is filtration loss from the pond. In its turn, the filtration loss includes two components:

$$Q_f = Q_d + Q_b,$$

where Q_d is water discharge rate due to seepage to drainage channels, and Q_b is the subsurface discharge rate through the bottom of the pond that is not intercepted by drainage channels (FIG. 4).

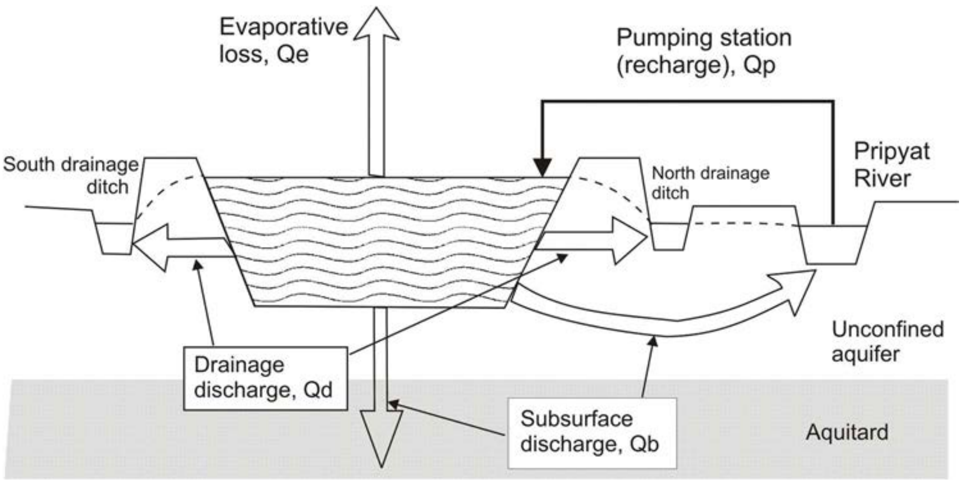


FIG. 4. Water balance in the ChNPP cooling pond.

In order to maintain the water level in the cooling pond the following condition needs to hold:

$$Q_p = Q_t,$$

where Qp is the rate of pond replenishment by the water pumped from Pripyat River.

As already mentioned, the most uncertain parameter from the listed above components of the pond water balance is the water discharge rate through the bottom of the pond (Q_b), as this parameter cannot be measured directly.

However, this parameter can be determined from the cooling pond water balance as:

$$Q_b = Q_t - Q_e - Q_d.$$

In the above equation evaporation losses from the pond Q_e can be estimated from atmospheric evaporation models (e.g. Penman equation) utilizing the measured meteorological parameters. The discharge rate of drainage ditches (Q_d) can be estimated from monitoring of flow rate in streams, which originated from drainage ditches, using standard hydrological gauging techniques.

The total water loses from the pond (Q_t) can be determined using two alternative methods:

(1) from electricity consumption by the pumping station, or

(2) by observations of the rate of water level drawdown in the pond during the periods when the pumping station was shut down (e.g. for servicing of the equipment) and consequently there were no water recharge to the pond.

The method relying on pump electricity consumption data, however, can lead to large errors due to clogging of the pumping station water-intake grills, leading to significant overestimation of the total loss (Q_t) and eventually of the seepage loss (Q_b) [11]. Therefore, the most reliable estimates of the cooling water balance were obtained by observations of the rate of water level drawdown in the pond in the course of the controlled experiment [5, 13].

The experiment on controlled drawdown of the water level in the cooling pond in order to estimate seepage losses was carried out in in July–August 2001 when pumping station was purposefully shut down for 13.5 days. During this period, the decline of water level in the pond totaled 24 cm. Results of experiment are summarized in TABLE 3.

TABLE 3. RESULTS OF THE EXPERIMENT ON ESTIMATION OF THE SEEPAGE LOSSES FROM THE COOLING POND 26.07.2001–09.08.2001 (*based on data* [13])

Parameter	Value
Input data	
Cooling pond surface area, km^2	22
Duration of the experiment, days	13.5
Water level drawdown, cm	24±1
Evaporation (water layer) (Qe), cm	6.9±1.5
Discharge rate of drainage ditches (Q_d), m^3/s	2.0±0.2
Resulting parameter estimates	
Total seepage loss (Q_f), m^3/s	3.2±0.3
Subsurface seepage loss that is not intercepted by drainage ditches (Q_b), m^3/s	1.2±0.4

Based on results of the experiment, the total seepage loss from the pond (in conditions of the mean water level in pond of 110.8 m a.s.l.) was estimated at Q_f = 3.2±0.3 m^3/s (~ 101 10^6 m^3/y), while subsurface seepage which was not intercepted by drainage ditches was estimated at Q_b = 1.2±0.3 m^3/s (~ 38 10^6 m^3/y). Thus, about 60% of seepage losses were intercepted by the drainage ditches, while about 40% of filtration from the pond was going in subsurface directly to Pripyat River.

It can be seen that in conditions of maintaining of the “normal operation level of water” in the pond (~ 111 m a.s.l.) without the heat load on the pond from operating reactors, the seepage losses from the pond (~101 10^6 m^3/y) essentially dominated the evaporation loss (~ 5 10^6 m^3/y).

2.1.5. Bathymetry and bottom sediments

2.1.5.1. The relief of the cooling pond bottom (bathymetry)

The relief of the bottom of the cooling pond was studied in the course of the detailed depth survey carried out in 2001 [5, 14]. It was further précised in the following years [6, 8].

In 2001 the depth distribution was determined using echo-sounder at a detailed set of the 200 m spaced profiles across the pond with the distance between sampling points in different profiles of ~ 30–50 m (FIG. 5). The resulting bottom topography distribution obtained by means of spatial interpolation of individual measurements is shown in FIG. 6.

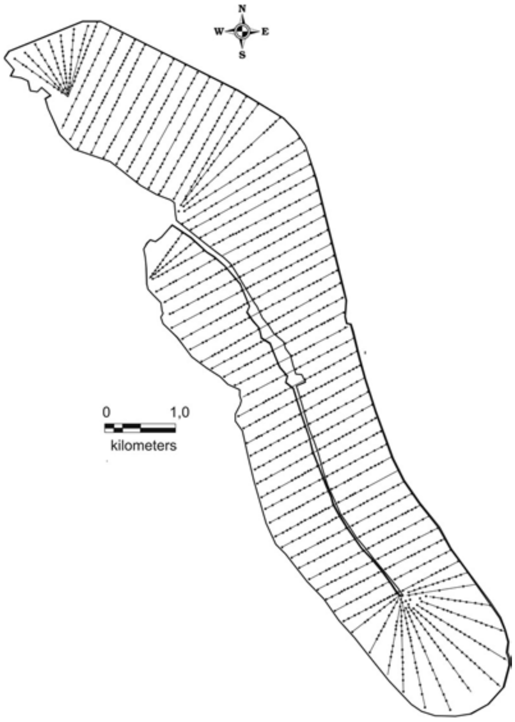


FIG. 5. Points of the 2001 echo-sounding survey of the bottom of the cooling pond (the total number of measuring points is 2217).

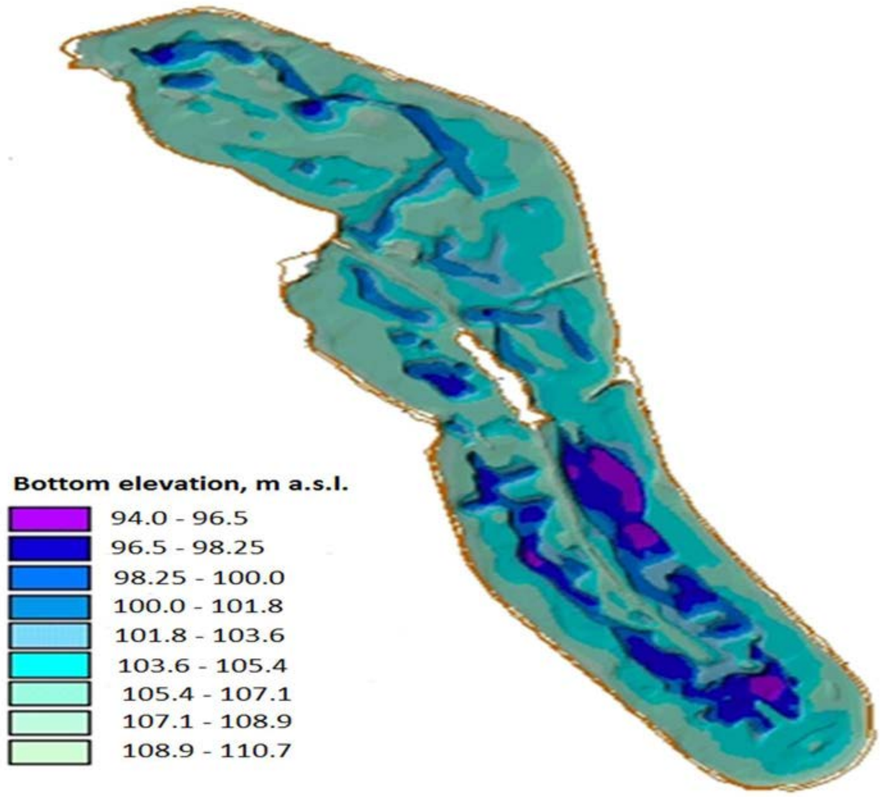


FIG. 6. Bottom topography in the cooling pond (based on surveys carried out in 1999–2001).

The bottom relief of the cooling pond is rather complicated. Significant part of the bottom in the depth range up to 7 m represents the surface of the former floodplain (depth range 4–7 m) as well as the inner slope of the cooling pond dam (depth range 0–4 m). The deeper parts of the pond bottom with depth up to 16–17 m are related to old channel of the Pripyat River (which existed here before the construction of the pond), former flood plain lakes as well as sand quarries, which were used for construction of the cooling pond dam using hydraulic fill method (in the southern part of the pond). In addition, the bottom topography reflects remains of the submerged dams related to the first stage of the cooling pond in middle part of the reservoir.

Information on depth distribution of the cooling pond based on most recent studies is summarized in TABLE 4. It can be seen that areas with depths of 7.5 m and less occupy about 70% (~ 15.8 km^2) of the cooling pond. These areas can be potentially exposed in case of the drawdown of level in the cooling pond in the course of its decommissioning.

Graph showing the dependence of the cooling pond water surface area from the water level in the pond is presented in FIG. 7.

TABLE 4. CORRESPONDENCE BETWEEN THE DIFFERENT DEPTH RANGES IN THE COOLING POND, BOTTOM SEDIMENT TYPES AND RESPECTIVE BOTTOM AREAS (*based on data* [15])

Depth range, m	Prevailing type of bottom sediments	Bottom area, km^2	Fraction of the total cooling pond bottom area, %
0–3.5	Sand	2.1	9.6
3.5–7.5	Silty sand	13.7	62.6
7.5–10	Silt with admixture of sand (sandy silt)	2.1	9.6
10–12	Silt	1.7	7.8
> 12	Silt	2.3	10.5

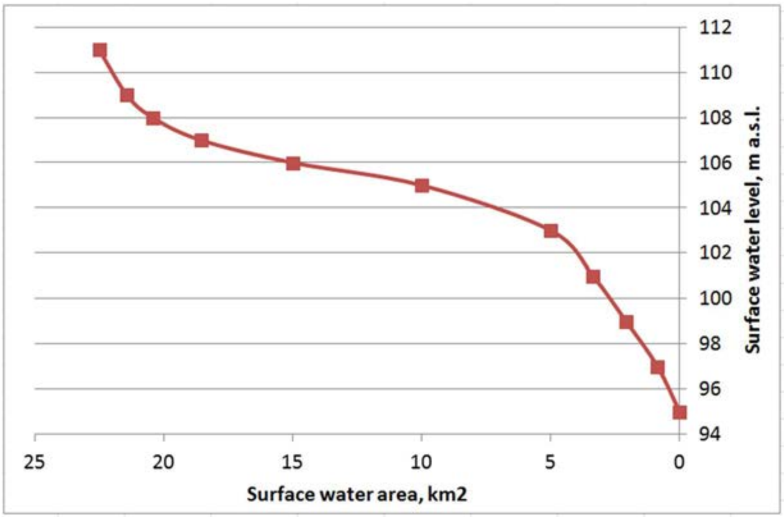


FIG. 7. Dependence of the cooling pond water surface area from water level in the pond (based on surveys carried out during 1999–2001).

2.1.5.2. Bottom sediment types and their distribution

Analyses carried out in [4, 16] suggest that since the construction of the cooling pond, active transformation of primary flooded soils and formation of bottom sediments took place, including process of silt particle resuspension, sedimentation, and migration of silt material from shallow to deeper areas (trans-sedimentation process).

During operational period of the ChNPP, circular velocities of flow of cooled water in the reservoir constituted on average 0.01–0.02 m/s [4]. After closure of ChNPP, water currents in the reservoir were determined only by natural environmental conditions, such as strong winds causing the wave process. Waves and wave-induced deep compensatory currents within the shallow waters of the reservoir (up to 5–7 m depth) facilitated washing-out of fine-grain bottom sediments and its sedimentation into deeper depressions of the pond bottom. Silt particles that settle in shallow depths may be repeatedly resuspended, and eventually settle at depths of 8–10 m or more [16].

Bottom soils at shallow depth are usually represented by sandy materials with some admixture of silt fractions. At depth more than 7 m in the deeper depressions of the bottom the silty sediments are dominant (see TABLE 4).

Due to trans-sedimentation process the thickness of silt layer at shallow depth (e.g. up to 5–7) was relatively small (1–5 cm), while at large depth (> 10 m) it often reached from several tenths of centimeters up to 1 m [4, 5, 16,17].

Map of distribution of different types of bottom sediments in the cooling pond based on analyses of Ukrainian Hydro-meteorological Institute (UHMI) is shown in FIG. 8.

The following definitions of different sediment types, based on the percentage of silt particles (i.e. particles < 0.01mm diameter) were used.

1. Sand: less than 1% of particles < 0.01mm;

2. Silty Sand: 1–5% of particles < 0.01mm;

3. Sandy Silt: 5–10% of particles < 0.01mm;

4. Silt: >10% of particles < 0.01mm.

Based on mass balances of different sources of silt material to the pond (e.g. input with the inflowing water of Pripyat River, eolian transport, bio-production etc.) it was concluded in [16] that the main factor of silt accumulation in the cooling during the post-accident period was trans-sedimentation process caused by continued transformations of the primary flooded soils of the pond bottom.

Olkhovik et al., [18] estimated silt accumulation rate in the pond at 1.7±0.6 g/(cm^2 year). Position of the activity peak in cores of bottom sediments collected from the cooling pond in 1999 suggests that the sediment accumulation rates in the cooling pond during the post – accident period constituted for different areas of the pond bottom from 1.5–7.5 cm/year, or in terms of mass flux 0.6–2.5 g/(cm^2 year) [16]. Similar estimate of silt sediment accumulation rate in the pond of 5 cm/year was derived by Pirnach [19] based on analyses of ^{137}Cs peak in core sample collected from the cooling pond in 2002.

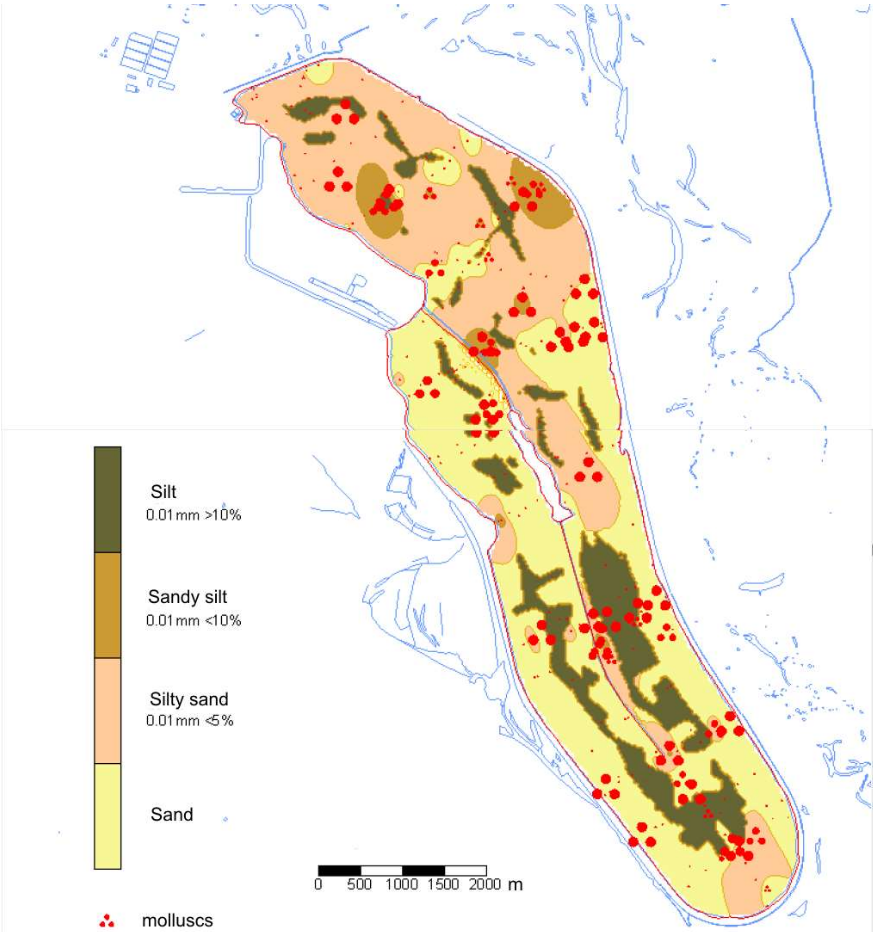


FIG. 8. Map of distribution of different types of bottom sediments in the cooling pond based on analyses of the Ukrainian Hydro-meteorological Institute (based on [7]).

2.1.6. Temperature regime and hydrochemistry

At the time when ChNPP Units 1, 2 and 3 operated, the temperature of the water released by outflow channel varied through the year from (12.5–37.5)ºC. In the course of circular movement from outflow channel to inflow channel the water was cooled on average by ~ 10ºC. The water temperature in the inflow channel of the pond was by (1–3)ºC higher compared to temperature of water in Pripyat River [4].

After stopping of the last ChNPP reactor in 2000, the temperature regime of the pond became similar to that one of natural water bodies. Such temperature regime is characterized spring-summer direct temperature stratification (higher temperatures in upper strata) in the water body and reversed temperature stratification in winter, which is characteristic to most water bodies in moderate latitudes [20].

The chemical composition of water in the cooling pond was similar to the Pripyat River, which served the source for replenishing the pond to compensate for seepage and evaporation losses. Data on chemical composition of water of the cooling pond in 1991–2002 (operation period of ChNPP) and 2012–13 (post-operational period) as well as chemistry data for Pripyat river are shown in TABLE 5. The concentration of total dissolved solids in pond water ranged from 250 to 350 mg/l, while the major ions in water were calcium and bicarbonate ion [20].

Major ion concentrations in the pond have not changed significantly after ChNPP closure, and were close to composition of Pripyat River. Observed decrease in SO_4^{2-}, NH_4^+ and PO_4^{3-} concentrations in pond surface water system can be explained by stopping of discharges of waste waters (e.g. from laundry and decontamination workshops) from the ChNPP after stopping the last reactor unit 2000 [8].

TABLE 5. CHEMICAL COMPOSITION OF THE WATER IN THE COOLING POND IN COMPARISON TO PRIPYAT RIVER (*based on data* [20])

Sampling location, observation period	pH	Chemical constituent, mg/l							
		Ca^{2+}	Mg^{2+}	Na^++K^+	SO_4^{2-}	HCO_3^-	Cl^-	NH_4^+	PO_4^{3-}
Cooling pond, 1991–2002	7.7–8.8	40–60	7–16	10–20	20–120	130–230	20–30	0.7–1.5	0.1–1.5
Cooling pond, 2012–2013	7.3–8.1	36–45	12–23	6–16	20–28	140–170	20–28	0.1–0.3	0.01
Pripyat River, 2013.	7.45	47	7	15	27	150	20	0.38	0.03

2.1.7. Technological water reservoir for replacement of the cooling pond

To start decommissioning of the cooling pond, it was necessary first to create an alternative source for supply of the ChNPP with technological water and water for firefighting purposes.

The project design for the replacement technological reservoir was developed in 2011. The project design foresaw creating of the smaller reservoir on the basis of the inflow and outflow channels of the cooling pond (FIG. 9). The bottom of these channels has been initially lined with concrete slabs (at the time of cooling pond construction).

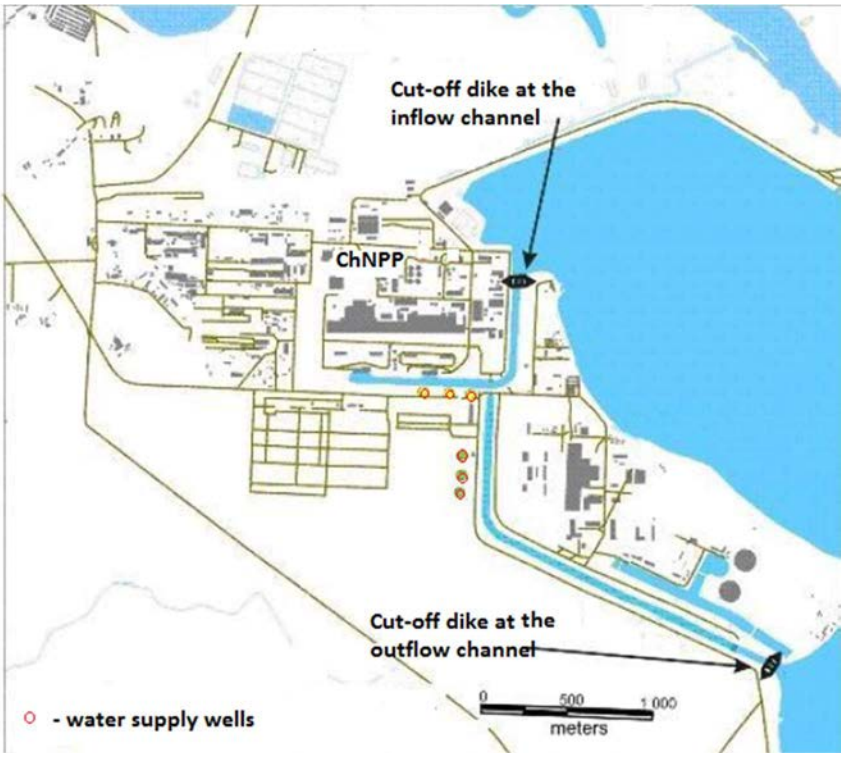


FIG. 9. Scheme of the technological reservoir for replacement of the cooling pond based on inflow and outflow channels of the pond.

In accordance with the project design, the channels were separated from the main water body of the pond by means of the two "cut-off dikes" with hydraulic shutters allowing regulating the water level. The operational water level in the new technological reservoir is 111.0±0.5 m a.s.l.; the water area of the reservoir is ≈27 ha; the volume of water is $\approx 1.2 \times 10^6$ m^3 [8].

The recharge of the new technological water reservoir was provided by 6 groundwater intake wells with the depth of 35 m extracting water from the unconfined aquifer in sandy Quaternary deposits (FIG. 9). The total debit rate of groundwater intake wells is 240 m^3/hour.

Construction of the new technological water supply system started in 2012, and was completed in August 2013 [8].

2.2. ENVIRONMENTAL CONDITIONS

This section presents brief information on the environmental conditions of the cooling pond, thus providing the context for the subsequent sections discussing radioactive contamination and remedial analyses. The main sources of information and data for this section are reports [4, 5, 8].

2.2.1. Climate

The Chernobyl NPP site is located within the area with a moderate-continental climate that is formed in process of interactions of the western (marine) and eastern (continental) influences. Average annual air temperature is +6.6ºC. Average relative air humidity is 75–80%.

The coldest month is January with the average monthly temperature of -6.8ºC. The warmest month is July with the average monthly temperature of 19.2ºC.

The territory is characterized by positive meteoric water balance: average annual precipitation exceeds evaporation Atmospheric precipitation mainly occurs during the warm season (from June to August). The mean annual rainfall is about 600 mm. In wet years, the amount of precipitation can be as high as 829 mm; and in dry (drought) years precipitation can be as low as 336 mm.

Average yearly wind speed is 4.2 m/s. The distribution of wind speeds by frequency is as follows: 0–3 m/s (47.8%); 4–7 m/s (41.9%); 8–11 m/s (7.7%); > 12 m/s (2.6%).

Main meteorological parameters of the study area are summarized in Appendix II. Additional details on meteorological conditions and parameters of ChNPP site are provided in [4].

2.2.2. Geology and Hydrogeology

2.2.2.1. Regional geological and hydrogeological settings

Geological structure of the study site described below is based on references [21, 22].

The studied territory is located in tectonic respect within the North-western slope of the Ukrainian crystalline shield (basement rock). The roof of basement rock is situated at 20 to 80 m a.s.l., and the thickness of the sedimentary cover varies from 130 to 190 m.

The sedimentary cover consists of marine and continental rocks of all systems of Mesozoic and Cenozoic erathems, which slightly dip to the East and Southeast. The geology structures of the sedimentary cover (from bottom to top) are as follows. The Upper and Middle Jurassic formations are represented by sands, clays, marls, siltstone, and limestone. Chalk deposits atop the Jurassic formations are represented by three suites: Cenomanian suite formations (K_2cm) consist of water-saturated fissured sandstone and sands overlain by low permeable marl-chalk formations of Turonian, Coniacian and Santonian suites (K_2t-cn-st). The total thickness of chalk formation is about 100 m. Chalk deposits are overlain by saturated glauconite-quartz sands of Kanev (P_2kn) and Buchak (P_2bc) Eocene suites above which lie low permeable carbonate siltstone-clays (most frequently referred to in literature as marl and clay) of Kiev suite of Eocene (P_2kv). Sandy alluvial Neogene (N_2) and Quaternary formations of Pleistocene, and Holocene (Q_{1-4}) lie atop the Kiev formations (FIG. 10 A and B). The thickness of Quaternary sandy alluvial formations is about 25–30 m.

The Quaternary sandy formations represent the near field geological environment, which is of most interest for analyses of hydrogeological conditions of the ChNPP cooling pond. The mentioned deposits host the unconfined aquifer, which is directly influenced by the water seepage from the pond. The sandy deposits of the Kanev and Buchak suites of Eocene host confined aquifer. These formations are described in more detail in the next paragraph.

Details on site geology can be found in [21–23].

2.2.2.2. Local geological and hydrogeological settings

The river flood plain at the cooling pond site is composed of sandy alluvial deposits of Pripyat River with the total thickness of 18–20 m. These deposits host unconfined aquifer in Quaternary deposits, which is the first aquifer unit from the surface.

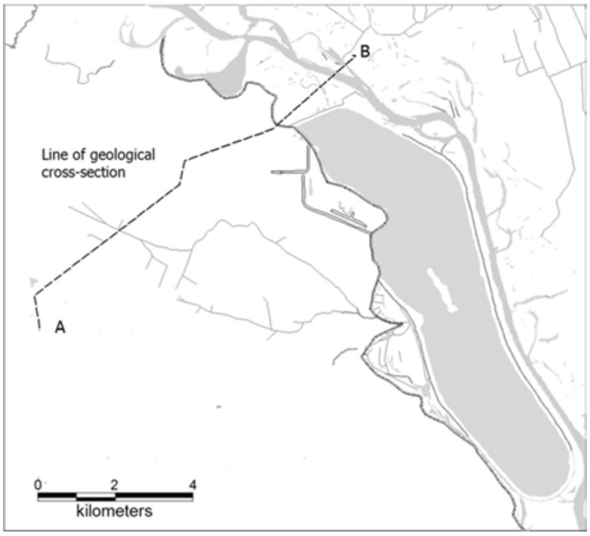
The alluvial sediments are represented by fine and medium quartz sands (the sand median grain size is 0.1–0.25 mm). The strata of Quaternary deposits are mainly composed of deposits of alluvial channel facies, which are represented by light-grey and yellowish-gray fine to medium grained quartz sands. Alluvial sediments of dead-channel facies can be often encountered within the former channels of Pripyat River, as well as in the form of lenses within the strata of the sediments of channel facies. These sediments are represented by fine silty dark grey sands and sandy loam materials. The sediments of the wash-out (basal) facies are episodically encountered in the lower part of the geological section. These sediments are represented by coarse and medium-grained gray sands with gravels and pebbles (up to 5% content). The thickness of basal layer varies from 0.5 m to 3 m [12]. Example of the geological cross-section of the strata of Quaternary alluvial deposits at cooling pond site is described in TABLE 6.

The alluvial Quaternary deposits of the floodplain of Pripyat River are characterized by generally high hydraulic conductivity values. The hydraulic conductivity of medium-grained sands was estimated at 9.6 to 27 m/day (with the average value of 20 m/day). The fine-grained sands were characterized by hydraulic conductivity values of 0.8 to 11.8 m/day (with the average value of 5 m/day). The recommended vertically averaged value of hydraulic conductivity for alluvial sandy deposits at cooling pond site is 12–15 m/day [12].

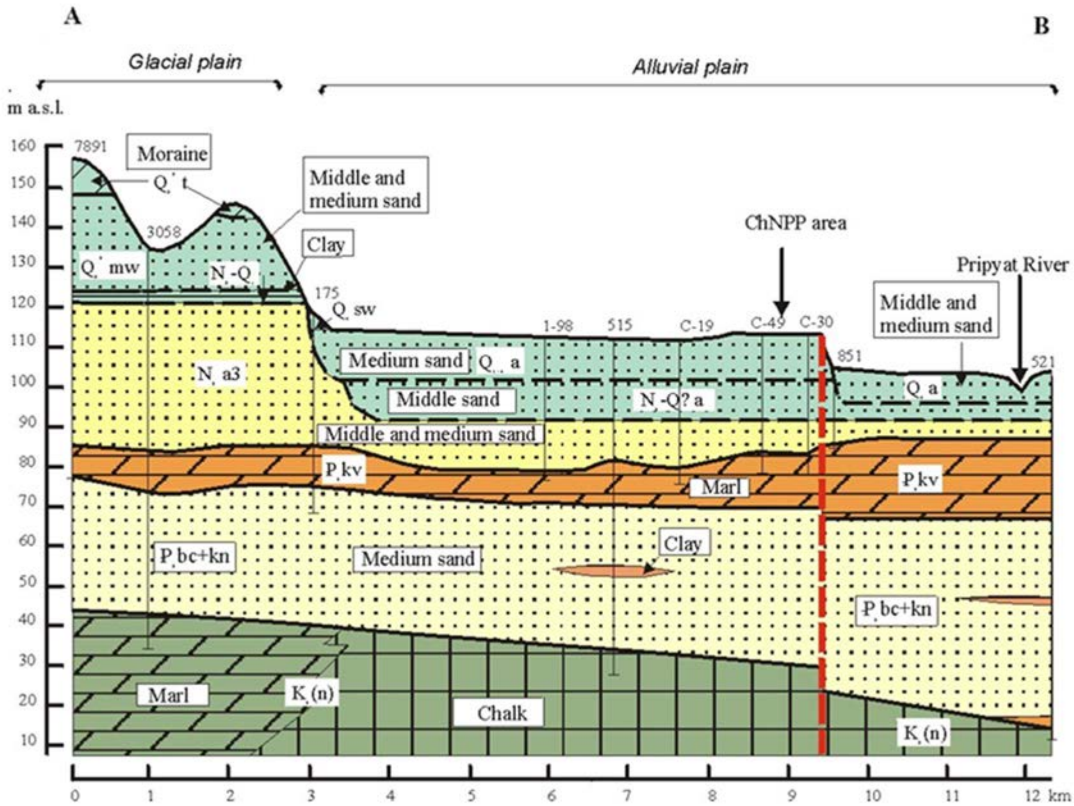
Clay marl deposits of the Kiev suite of Eocene compose the first regional aquitard, which separates the unconfined aquifer and confined aquifer in the Eocene sandy deposits. The thickness of the Kiev marl layer in areas adjacent to the cooling pond is 8–12 m. According to pump-tests and model calibration studies the hydraulic conductivity of marl layer falls within the range from 2×10^{-4} to 2×10^{-2} m/day, the higher values being more typical for the river floodplain areas [12, 21]. The confined aquifer is composed of marine deposits of Buchak and Kanev suites of Eocene, represented by fine sands with the inter-layers of sandstone, aleurolite and clay. The total thickness of the aquifer varies from 30 to 48 m. Hydraulic conductivity of Eocene deposits is estimated at 2.5–3 m/day [21].

TABLE 6. GEOLOGICAL SECTION OF ALLUVIAL DEPOSITS AT COOLING POND SITE (PK-127 OF THE DAM, WELL NO.5P) (*based on data* [12])

Depth interval, m	Description of the geological column
0–1.8	Backfilled medium sand and gravel
1.8–4.5	Fine and medium quartz sand with brownish color
4.5–19.5	Fine and medium quartz sand with light gray color
19.5–20	Coarse quarts white sand
20–21	Fine grained sand with admixture of blue-green marl material
> 21	Dense marl



(A)



(B)

FIG. 10. Geological structure of the ChNPP site; (A) Line of geological cross section, (B) Geological cross section of ChNPP site from SW to NE (based on data [23]).

2.2.3. Hydrology regime of Pripyat River

The ChNPP cooling pond was situated in the immediate vicinity of the Pripyat River, and had the potential to influence the river water quality through the seepage of contaminated groundwater, or by direct release of water in case of the failure of the dam.

The Pripyat River is the largest river crossing the Chernobyl Exclusion zone (ChEZ). The catchment basin of the river upstream from the city of Chernobyl is about 106,000 km^2. The length of the Pripyat River within the ChEZ is 780 km. The Pripyat River joins the Kiev Reservoir, which is one of the water reservoirs of the Dnieper River.

The Dnieper River is the major watercourse of Ukraine with the population in its basin of approximately 30 million (i.e. ~60% of population of the Ukraine).

During the construction of the cooling pond, the pre-existing riverbed of Pripyat River has been straightened, and the 11km non-lined channel was constructed along the dam of the cooling pond. The average width of the constructed river channel varies from 125 to 180 meters, and the average depth is from 3 to 5 m [4].

Snowmelt is the main source of the river recharge. The water flux in the river is greatest during the spring period in April to May, with 70% to 80% of the annual water flux passing during the spring flooding period. Minimal water flux is observed in winter period.

The average annual water flux in the vicinity of the City of Chernobyl is 420 m^3/s. The maximum water flux (with 1% probability) of about 6,000 m^3/s (which corresponds to the water level 110 m a s.l.). The minimum average daily river flow is ~ 60 m^3/s with the water level of 102.2 m a.s.l. [24].

During the peak of high waters (i.e. flooding), the maximum water velocity in the river may exceed 2 m/s in the riverbed, and reach 1 m/s or more within the flooded areas of the floodplain.

The cooling pond dam has been designed to withstand the water level in Pripyat River of 111.3 m a.s.l., which corresponds to flow conditions with the recurrence of 1 per 1,000 years, with the flux of 9,000 m^3/s.

It should be pointed out that the groundwater seepage from the cooling pond is significantly diluted upon mixing with the water flow in Pripyat River – Dnieper River system. It was estimated that seepage from the pond contributes less than 1% to the average annual flux of 420 m^3/s in Pripyat River near Chernobyl, and only 0.02% to the average yearly flow of 1400 m^3/s in the Dniper River near Kiev [11].

2.2.4. Aquatic habitat of the pond

Before the water level drawdown, the cooling pond represented a high-productivity aquatic ecosystem with a high degree of biodiversity of aquatic life of different trophic levels and ecological groups. Significant quantities of water plants (macrophytes), phytoplankton and zooplankton, phyto and zooperiphyton, zoobenthos and fish were present in the cooling pond.

The cooling pond ecosystem included both species populating the old riverbed of the Pripyat River as well as species purposefully introduced to the cooling pond for fish breeding purposes.

One of repeatedly expressed concerns was that lowering of the water level in pond might cause “ecological catastrophe” leading to mass perishing of fish, mollusks, etc. and resulting in deterioration of ecological situation in residual reservoir [4, 8, 20].

The study of transformation of the cooling pond aquatic ecosystem due to the pond decommissioning appears to be an interesting and challenging task from both applied and scientific points of view.

The Institute of Hydrobiology (IHB) of the National Academy of Sciences of Ukraine has carried out in 2012–2013 studies of in order to characterize the conditions of aquatic habitat in the cooling pond (e.g. amount of biomass and bio-productivity of different species) before the beginning of water level drawdown in the pond [25]. Results of these studies are summarized in Appendix III.

3. RADIOACTIVE CONTAMINATION OF THE COOLING POND

3.1. MECHANISMS OF CONTAMINATION OF THE COOLING POND AND RADIONUCLIDES OF CONCERN

3.1.1. Radioactive contamination of the pond before the Chernobyl accident

Earlier to the Chernobyl accident, radioactive contamination of cooling pond was caused by routine liquid and aerosol discharges from the nuclear power plant. According to the review of available data carried out in [4, 20, 26] ^{137}Cs activity concentration in the water of the pond in 1985 was 30–37 Bq/m^3, while ^{90}Sr activity concentration was 2–20 Bq/m^3. The contamination levels of bottom sediments in the pond with respect to ^{137}Cs in 1981 were as follows: for sand 25 Bq/kg; for silt 4.7×10^3 Bq/kg.

It should be noted that a rather serious radiation accident resulting in the release of radioactivity to the atmosphere occurred at ChNPP in 1982. However information on the contamination of the cooling pond as a consequence of the mentioned above accident is not available, and in any case related contamination levels were significantly lower compared to activity introduced to the pond in the course of Chernobyl accident on 26 April 1986 [4].

3.1.2. Radioactivity releases to the pond in the course of the accident

The radioactive contamination of the cooling pond in the course of the Chernobyl accident, which happened on 26 April 1986, was caused by the two main factors [4, 12, 27]:

- Atmospheric deposition of radioactive fallout on the water surface of the cooling pond, and

- Release to the pond of some ~ 5000 m^3 of highly contaminated water from the emergency cooling system of the ChNPP Unit 4, as well as water used in the course of the firefighting, which have flooded the basement premises of the power plant.

Large contamination related to the liquid release of activity from the plant is confirmed by the important bottom sediment contamination "hot spot" located at the mouth area of the outflow channel [4, 5].

WEISS et al. [4] further state that "it is a common knowledge that in the course of decontamination measures at the Chernobyl site probably contaminated equipment would be dumped into the pond". However no proofs of this statement have been provided in the aforementioned reference and/or in any other literature sources know to authors of this report.

3.1.3. Radionuclides of concern

In the early period after the accident high specific activity of the pond water and sediments was determined mainly by short-lived fission products, such as ^{131}I, ^{140}Ba, $^{103,106}Ru$, $^{141,144}Ce$, ^{95}Nb, ^{95}Zr etc. In the beginning of May 1986 the gross specific beta-activity of the water in the pond was about 4×10^4 Bq/l, where 80–90% of activity was caused by ^{131}I; the total radioactivity inside the pond was estimated at 5×10^{15} Bq [28].

With the decay of short-lived radionuclides, the ^{90}Sr and ^{137}Cs became the main radiologically important radionuclides in the water of the pond.

With regard to contamination of bottom sediments, the important dose-forming radionuclides are also transuraniuc (TRU) long-lived alpha-emitting radionuclides, which were present in radioactive releases from destroyed Unit 4: ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Am, which is the daughter product of ^{241}Pu. The mentioned TRU radionuclides generally have a low mobility in surface water and groundwater system of the pond, but may pose risk in case of drying up of bottom sediments following the water level drawdown in the pond.

3.1.4. Fuel hot particles in the cooling pond

Radioactive contaminants released to the pond were initially associated with "condensation" aerosol hot particles (enriched in volatile radionuclides such as ^{137}Cs and ^{106}Ru) as well as with hot particles with the matrix of the dispersed nuclear fuel of ChNPP Unit 4. In particular, ^{90}Sr, Pu and ^{241}Am isotopes were initially release to the pond almost exclusively in the form of fuel hot particles [29].

The subsequent migration behavior of radionuclides in the cooling pond was to large degree determined by release rates of radionuclides from fuel particles to mobile (e.g. water soluble, ion exchangeable) forms [11, 13, 29]. This subject will be discussed and analyzed further in the report.

3.2. BOTTOM SEDIMENTS

3.2.1. Redistribution of radioactivity in "water-bottom sediment" system in early period

In the early days following the Chernobyl accident radioactivity of water in the cooling pond was caused mainly by suspended hot particles. Based on data of surveys the γ-activity of water in the pond in mid-May 1986 in the northern (most contaminated) part of the cooling pond, it was of and order of ~ 10^4 Bq/L, while the total inventory of radionuclides in the cooling pond at that time was estimated at ~ 2000 TBq.

Sedimentation of the hot particles, sorption of dissolved radionuclides on bottom sediments, and radioactive decay of the short-lived radionuclides resulted in a sharp decrease of γ-activity of water in the pond. By the end of 1986, the γ-activity of water in the pond decreased to ~ 10^2 Bq/L [26, 30].

By the end of 1986 about 95% of ^{137}Cs and 99% of ^{90}Sr in the cooling pond system were accumulated in the bottom sediments [4].

3.2.2. Peculiarities of spatial distribution of radionuclides in the bottom sediments

During the post-accident period, series of sampling surveys of radioactive contamination of bottom sediments of the cooling pond were carried out, which included collecting of bottom sediments cores and their radiometric analyses [4–6, 8, 27, 28, 31].

The most systematic and comprehensive surveys utilizing the state-of-the art bottom sediment sampling equipment were carried out in 1999–2012.

In the course of survey carried out in 1999, sampling was carried on 10 different locations representing different depth ranges and different types of bottom sediments in the cooling pond. In each location vertical distribution of radionuclides in collected cores was determined [4, 16].

A larger scale bottom sediment survey was carried out in 2001 when sediment cores were collected at 83 locations; from these 44 cores were further subdivided in separate discs and were analysed for radionuclide content. For the rest of cores visual description (e.g. sediment lithology, thickness of silt layer etc.) was provided [5]. Additional cores to precise bottom sediment contamination patters in the pond were collected in 2002–2005 [6] and in 2012 [15].

It was established that mechanisms of radionuclide accumulation and redistribution within the bottom sediments of the cooling pond are closely related to depth, genesis and hydrodynamic evolution mechanisms of respective bottom sediment types [5, 6, 16].

Contamination levels and patterns of vertical distribution of radionuclides in sediments differed essentially in the shallow parts and deep parts of the pond (e.g. depth > 11 m, with the stable accumulation of silt material).

3.2.2.1. Shallow areas (0–7 m)

Within the indicated depth range, several types of bottom sediments were encountered: sand, silty sand and sandy silt (see section 2.1.5.2).

Sandy deposits without admixtures of silt were encountered within the depth from 0 to 3.7 m. In these areas main radioactive contamination was usually contained in the upper 10–15 cm sediment depth range (FIG. 11).

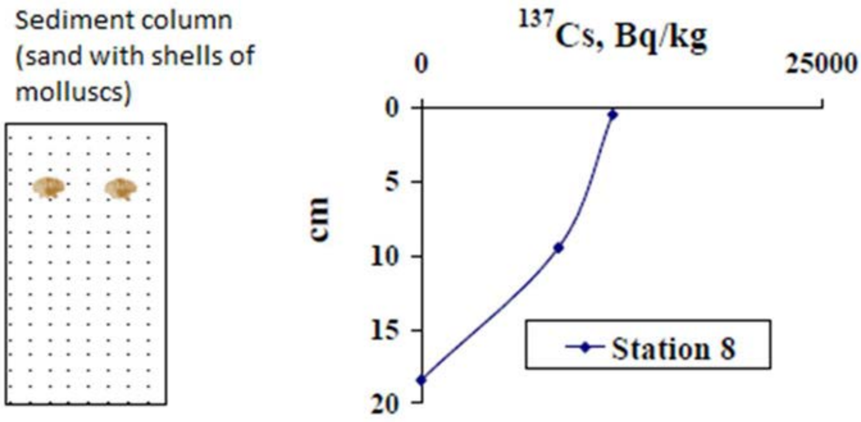


FIG. 11. Vertical distribution of ^{137}Cs in sandy sediments in shallow area of the cooling pond in 2001 (based on data [5]).

Silty sands (see definition of sediment types in section 2.1.5.2) were mainly present within the depth range of 3.7 to 5 m, while sandy silts were wide spread at depth > 5 m. Within the depth range of 5–7.5 m the thickness of silt layer on top of sand (or transformed primary soils of pond bottom) usually did not exceed 1–6 cm.

In case of the described above types of bottom sediments, approximately 80–90% of the radionuclide activity was typically concentrated in the upper 5 cm layer of the sediment. In deeper layers, the content of radionuclides decreased to levels observed prior the accident (FIG. 12).

It should be pointed out that in some shallow areas contamination hot spots were present with much higher contamination levels than average values for the respective sediment depth range. In particular, such contamination hot spots were encountered in the northern part of the pond (presumably contaminated by atmospheric radioactive fallout to the water surface) and in the area of the outflow channel of the pond (presumably contaminated by liquid releases to the pond in the course of the accident) [5].

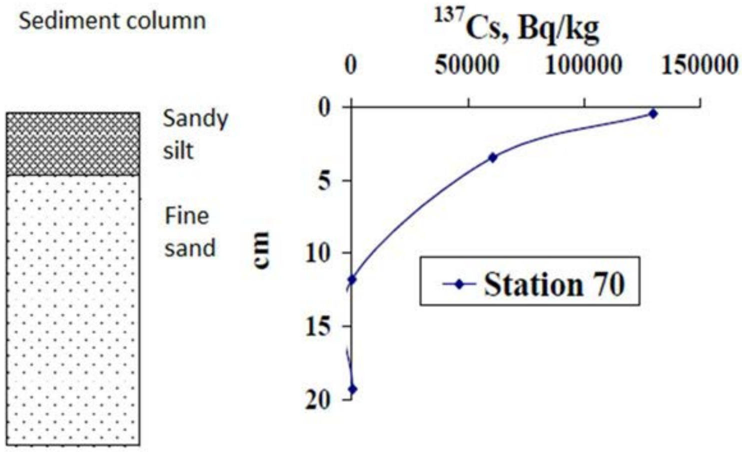


FIG. 12. Vertical distribution of ^{137}Cs in sandy sediments with thin silt layer in shallow area of the cooling pond in 2001 (based on data [5]).

3.2.2.2. Deep areas

Parts of pond bottom with depths in the range of 7.0–10.0 m usually represent the inclined banks of the relic channels of Pripyat River and / or of the former sand quarries. Due to inclined geometry these bottom areas usually do not accumulate silt material. Stable silt accumulation usually took place at depth > 10 m.

The deep areas were characterized by the highest levels of radionuclide accumulation in bottom sediments. Here vertical profiles of radioactive contamination of silt cores were characterized by a relatively even distribution of ^{137}Cs activity in the sediment layers deposited after the Chernobyl accident (FIG. 13). In such areas silt deposits contained the highest activity concentrations of ^{137}Cs in the range from 250–700 Bq g^{-1} [5, 16].

Activity profiles of other radionuclides (^{90}Sr, ^{241}Am and Pu isotopes) in bottom sediments usually showed correlation with ^{137}Cs distribution [16, 19]. Example combined depth profile of ^{137}Cs, ^{90}Sr and ^{241}Am in silt bottom sediments of the cooling pond from the deep area in the southern sector of the pond is shown in FIG. 14.

It was found that while ^{137}Cs specific activity in the silt in deep areas of the cooling pond showed generally similar contamination levels (in the range of 360 – 700 Bq/g) in different areas of the pond, the specific activity of ^{90}Sr in silt material in the same areas varied in much wider range across the pond (4 – 48 Bq/g, i.e. within the one order of magnitude). Thus, geochemical factors and mechanisms governing accumulation of ^{137}Cs and ^{90}Sr in silt sediments in the deep areas of the cooling pond likely were different and radionuclide – specific [5].

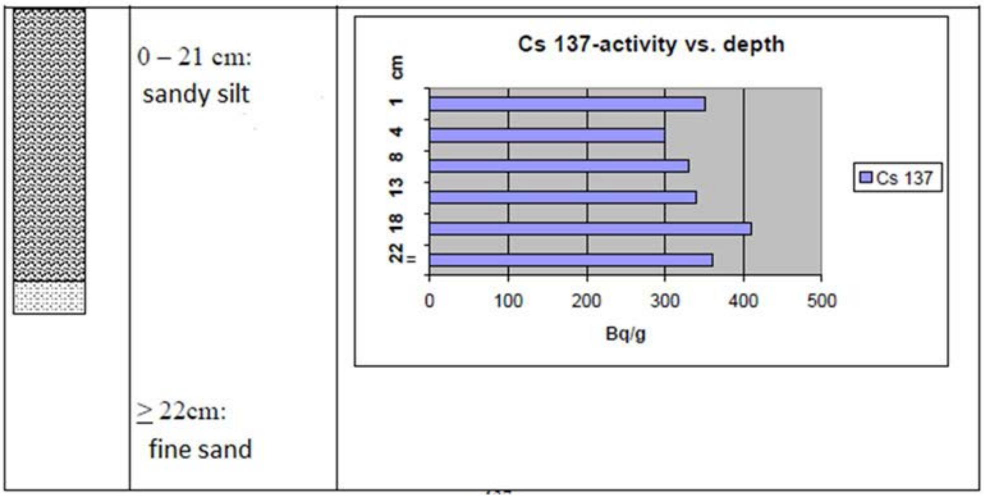


FIG. 13. Vertical distribution of ^{137}Cs in silt sediments in deep area of the cooling pond (depth 11 m) in 1999 (based on data [5]).

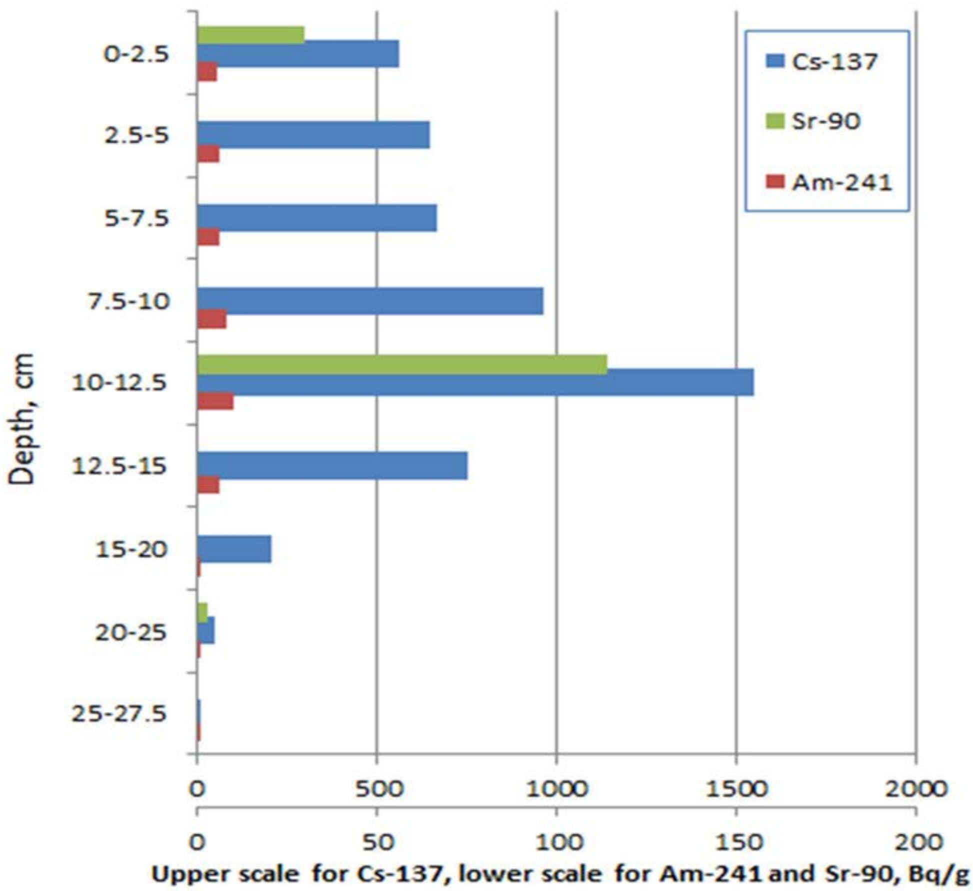


FIG. 14. Vertical distribution in of radionuclides in silt bottom sediments of the cooling pond from the deep area in the southern sector of the pond (depth >12 m) in 2002 (sampling station St.2) (based on data [19]).

Statistically significant correlation between thicknesses of the silt layer containing ^{137}Cs, ^{241}Am, $^{239,240}Pu$, and the contamination density of bottom sediments was usually observed, as shown in FIG. 15 [5, 16]. This is evidently related to adsorption of the mentioned radionuclides on the silt particles from the pond water column, and subsequent redistribution (due to trans-sedimentation process) to deeper pond areas.

For ^{90}Sr only weak positive correlation of contamination density with thickness of silt layer was observed in 1999–2001 (FIG. 15). This suggests that sorption on silt particles and subsequent deposition to deep areas was a less important re-distribution mechanism for ^{90}Sr in the pond compared to radiocesium and transuranic radionuclides (due to lower ^{90}Sr sorption distribution coefficient Kd values on silt material).

Radionuclide accumulation by sedimentation in the form of small hot particles (possibly attached to carrier silt particles) also likely took place, a ^{90}Sr and TRU ratios in columns of bottom sediment often showed ratios close to Unit 4 nuclear fuel ratios.

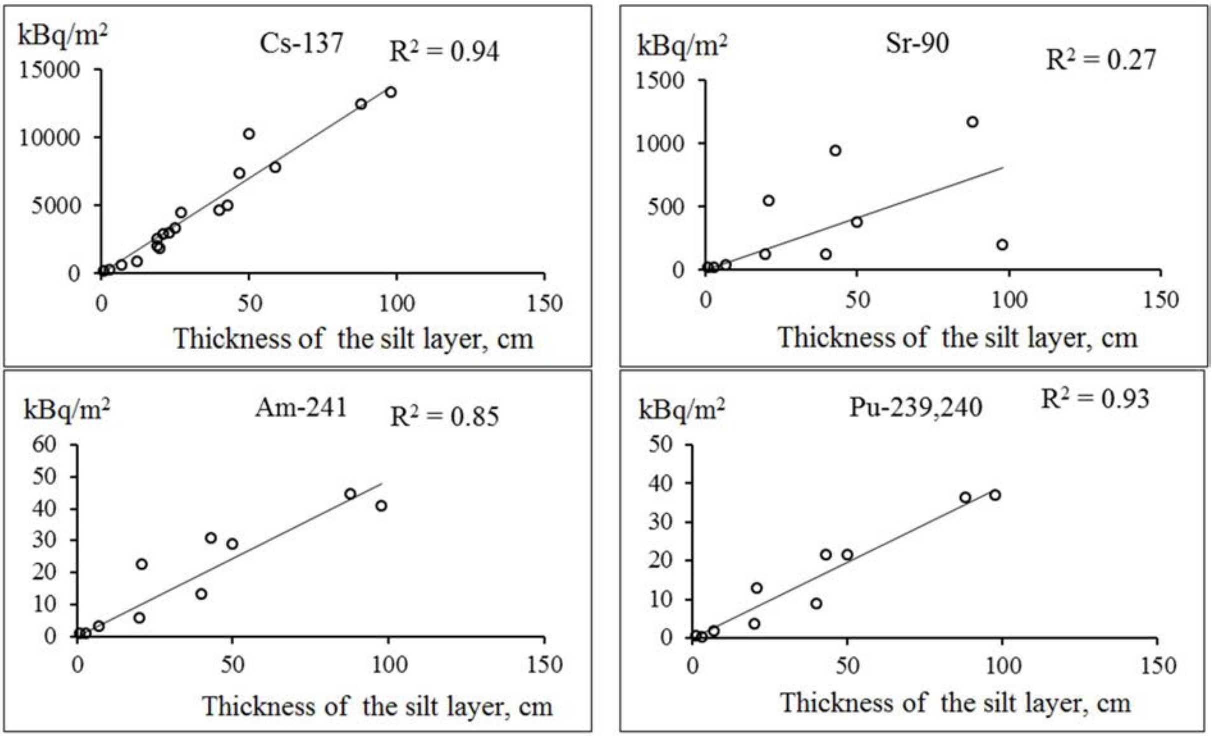


FIG. 15. Correlation between thickness of silt sediments and bottom sediment contamination densities by main radionuclides in 1999 (based on data [16]).

3.2.3. Inventory of radionuclides in the bottom sediments

Estimates of radionuclide activity inventories in bottom sediments of the cooling pond from different surveys are summarized in TABLE 7 (for comparison purposes all activity data are decay-corrected to 2012).

It can be seen that there are noticeable discrepancies in the radioactivity inventory estimates for the cooling pond bottom sediments from different surveys showing difficulties in accurately estimating such radioactivity inventories due to spotty character of contamination of bottom sediments (see TABLE 7).

The early study of bottom sediment contamination carried out in 1986–1989 did not properly took into account bottom sediment topography, and used simplified interpolation schemes, therefore the resulting estimates of radionuclide inventory in bottom sediments were rather approximate [6, 16].

A series of systematic surveys of bottom sediments of the cooling pond in 1999–2012 have led to establishing of the database of results from these surveys in the Ukrainian Hydro-Meteorological Institute (UHMI). By 2012, this database incorporated data on about 1000 samples of bottom sediments, which have been collected from the cooling pond by different organizations [15, 32].

TABLE 7. RESULTS OF STUDIES ON CHARACTERIZING OF RADIONUCLIDE DISTRIBUTION AND INVENTORY IN THE BOTTOM SEDIMENTS OF THE COOLING POND OF THE CHNPP (ALL ACTIVITY DATA ARE DECAY CORRECTED FOR 2012)

Year of survey	Report documenting survey	^{137}Cs inventory, TBq	^{90}Sr inventory, TBq	^{239,240}Pu * inventory, TBq	^{241}Am inventory TBq
1986	Egorov et al. [27]	90 – 158 **	41***	NA	NA
1989	Shi [31]	100	16.5	0.8	NA
2001	Buckley et al. [5]	164±32	24±9	0.53±0.19	1.1±0.4
2005	Smith et al. [6]	236±47	36±9	0.73±0.25	NA
2012	Voitsekhovitch et al. [16]	260±80	55±11	1.6±0.6	3±1

Notes: *in addition to transuranic radionuclides listed in TABLE 7, bottom sediments of the cooling pond contain also ^{238}Pu, which can be estimated from $^{239+240}$Pu activity using the ratio 0.42 (for 2012) (i.e. Pu isotope ratio in the fuel of the unit 4 of the ChNPP [5]); ** lower value of inventory was estimated by EGOROV et al. [27] based on bottom sediment survey, while the upper value was calculated assuming all ^{137}Cs measured in May 1986 in water column has been deposited to bottom sediments; ***activity of ^{90}Sr is estimated from inventory of ^{144}Ce assuming radionuclide activity ratio characteristic for Unit 4 fuel.

A special algorithm of spatial interpolation of activity data from point measurements to whole pond area was developed for interpretation of the cooling pond bottom sediment sampling results carried out in 2005 and 2012 [6, 15, 32]. This methodology accounted for bottom topography, as well as for the presence of different types of bottom sediments and sediment accumulation mechanisms. The data for shallow (depth 0–8 m) and deep areas (depth > 8 m) were processed separately to avoid large spatial gradients in activity concentrations on boundaries between these areas.

In particular, the analysis of ^{137}Cs inventory in bottom sediments and mapping of radionuclide distribution in the cooling pond carried out in [15] employed data from radiometric analyses 130 columns of bottom sediments, which penetrated the whole thickness of the contaminated bottom sediment layer. Estimation of ^{90}Sr inventory used as a basis the detailed ^{137}Cs data set. The ^{90}Sr inventory in bottom sediments was recalculated using experimentally determined area-specific ^{90}Sr:^{137}Cs activity ratios in bottom sediments.

These ^{90}Sr: ^{137}Cs ratios (varying from 1:1 to 1:10) were determined on 40 samples, and zoning of pond bottom in several sub-zones with regard to above ratios was carried out. Similar approach was applied to the TRU isotopes. Employing of such method has led to higher estimates of radionuclides inventories in bottom sediments for surveys carried out in 2005 and 2012 compared to previous similar estimates (see TABLE 7). As the objective was conservative assessment of activity inventory in bottom sediments, these data should be considered as an upper-end estimates [33].

Results of most recent estimation of inventory of ^{137}Cs and ^{90}Sr in bottom sediments of the cooling pond for different depth ranges carried out in the course of feasibility study for the decommissioning of the pond [15] are listed in TABLE 8, and are shown in FIG. 16 and FIG. 17. More than 50% of ^{137}Cs and ^{90}Sr activity is concentrated in the areas with depth more than 10 m, even though these areas represent only 18.1% of the pond bottom surface. The relatively shallow areas that are expected to be dried-up following water level drawdown (i.e. in the depth range from 0 to 7.5 m) occupy nearly 70% of the pond bottom, however they contain only ~ 20% of the total ^{137}Cs and ^{90}Sr inventory.

TABLE 8. ACTIVITY INVENTORIES OF ^{137}CS AND ^{90}SR IN BOTTOM SEDIMENTS OF THE CHNPP COOLING POND FOR THE REFERENCE DATE 2012 (*based on data* [15])

Depth range, m	Bottom are for specific depth range		^{137}Cs		^{90}Sr	
	km^2	%	TBq	%	TBq	%
0–3.5	2.1	9.6	10	4	2	4
3.5–7.5	13.7	62.6	43	16	10	18
7.5–10.0	2.1	9.6	65	25	13	24
10.0–12.0	1.7	7.8	61	24	13	25
> 12.0	2.3	10.5	81	31	16	29
Total	21.9	100	260	100	54	100

Estimated average bottom sediment contamination densities by ^{137}Cs at different depth of the cooling pond for the shallow depth range (i.e. from 0 to 7.5 m) are listed in TABLE 9. It should be pointed out that the cooling pond has a highly contaminated bottom sediment "hot spot" in the area of the outflow channel, where contamination was much higher than the adjacent level (FIG. 16 and FIG. 17). Average bottom sediment contamination densities in this area constituted: for ^{137}Cs – 9250 kBq/m^2; for ^{90}Sr – 5800 kBq/m^2 [15].

Average bottom sediments contamination densities by the sum of ^{238}Pu, ^{239}Pu and ^{240}Pu isotopes in the shallow areas of the pond constitute about 10–20 kBqm^2, while in the mentioned above hot spot Pu contamination reaches 59 kBq/m^2 [5, 15].

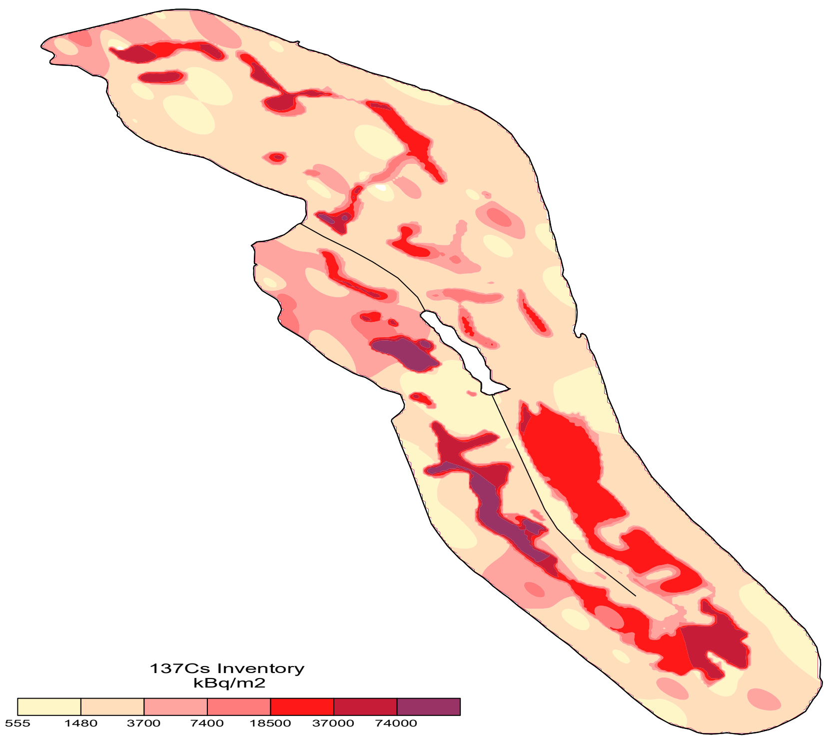


FIG. 16. Distribution of ^{137}Cs in the bottom sediments of the cooling pond (based on data of UHMI).

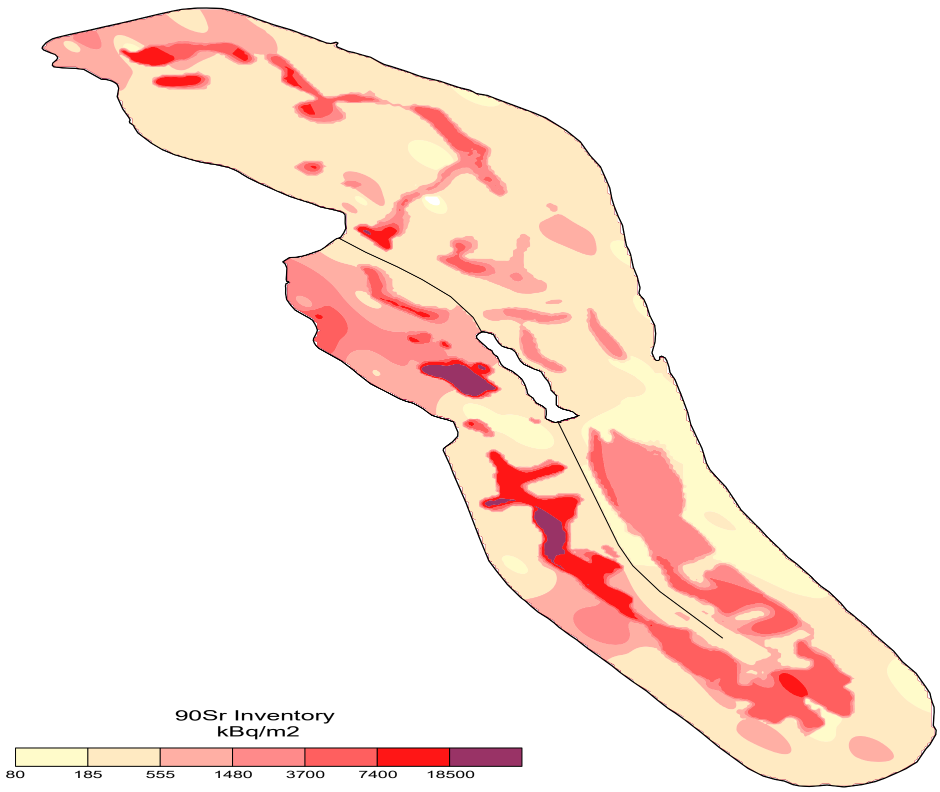


FIG. 17. Distribution of ^{90}Sr in the bottom sediments of the cooling pond (based on data of UHMI).

TABLE 9. AVERAGE BOTTOM SEDIMENT CONTAMINATION DENSITIES BY ^{137}CS AT DIFFERENT DEPTH OF THE COOLING POND, FOR 2012 (*based on data [15]*)

Depth range, m	Type of sediments	Average contamination of bottom sediments by ^{137}Cs, kBq/m^2
0 – 3.7	Sands	1470±450
3.7–5	Silty sands	1925±650
5.0–7.5	Sandy silt	2520±750

3.2.4. Radionuclide speciation in bottom sediments

Physical and chemical speciation of radionuclides in the bottom sediments of the cooling pond was studied in 1999 by method of sequential extractions. Exchangeable forms were determined by means of ammonia-acetate extraction. “Fixed” forms were determined by extracting the sample using mixture of concentrated hydrochloric and nitric acid. In parallel, the autoradiography using roentgen film was used to determine contribution of nuclear fuel “hot” particles (FP) to the β-activity of the studied sediment sample. Activity of each FP was estimated using empirical calibration dependence between the diameter of the image produced by the particle on the film and its β-activity [16]. Results of analyses for ^{137}Cs and ^{90}Sr are presented respectively in TABLE 10 and TABLE 11.

TABLE 10. CHEMICAL SPECIATION OF ^{137}CS IN THE BOTTOM SEDIMENTS OF THE COOLING POND IN 1999 (*based on data [16]*).

Sample ID	Depth, m	Type of sediment	Activity, Bq/g	Chemical forms of radionuclide , %		
				Water-soluble	Exchangeable	Fixed forms
VO-1	4.0	Silty sand	25.2	2.5	8.4	89.1
VO-4	13.0	Silt	429	0.15	2.5	97.4
VO-8	14.8	Silt	505	0.12	1.44	98.4
VO-9	14.1	Silt	464	0.1	1.5	98.4
V0-10	11.0	Silt	428	0.17	2.4	97.4

It can be seen that content of mobile chemical forms (water soluble, exchangeable) of radionuclides in all samples was rather low (less than 10%). Content of mobile forms of radionuclides in silts in deep areas (of an order of 1–2%) was lower than in sandy deposits in shallow area.

Auto-radiography data suggested that ^{90}Sr activity in bottom sediments was mostly associated with the undissolved fuel particles (> 90%). Data of autoradiography studies were in good agreement with the results of determination of “fixed” forms of ^{90}Sr using the sequential extraction method (see TABLE 11).

TABLE 11. CHEMICAL SPECIATION OF ^{90}SR IN THE BOTTOM SEDIMENTS OF THE COOLING POND IN 1999 (*based on data* [16])

Sample ID	Depth, m	Type of sediment	Activity, Bq/g	Chemical forms of radionuclide , %			Activity in FP, %
				Water-soluble	Exchangeable	Fixed forms	
VO-1	4.0	Silty sand	2.23	2.0	5.7	92.3	90±8
VO-4	13.0	Silt	38.2	1.1	1.4	97.5	91±6
VO-8	14.8	Silt	86.2	0.4	0.6	99.0	92±7
VO-9	14.1	Silt	87.4	0.35	0.98	98.7	96±4
V0-10	11.0	Silt	50.3	0.4	1.3	98.3	47±7

For ^{137}Cs, which initially likely was present in mobile forms associated with condensation component of radioactive fallout and liquid activity releases from the Unit 4 site, low content of mobile forms in bottom sediments by 1999 can be explained by secondary fixation on clay minerals, which is well known attenuation mechanism for this radionuclide [16].

Low content of mobile chemical forms of ^{90}Sr in silt sediments in deep areas is indicative of low dissolution rates of the UO_2 matrix fuel particles in these sediments caused by anoxic environment and close to neutral or slightly basic pH conditions [34]. (The pH range for the bottom sediments in the cooling pond was 7.3 – 8.5 [4]).

Better oxygenation conditions at shallow depth (promoting dissolution of FP) likely was the reason for higher content of mobile forms of ^{90}Sr in bottom sediments in shallow areas (e.g. sample VO-1; see TABLE 11). However, here ^{90}Sr can be easily leached from the thin layer of bottom sediments to the water column of the pond, which keeps the amount of mobile forms at relatively low levels.

Similar results on radionuclide speciation in bottom sediments collected from deep areas of the pond in 2002 were reported in [19]. For ^{137}Cs the amount of water soluble forms was 0.02–0.03%, while the amount of exchangeable forms was 2.2–2.9%; for ^{90}Sr the amount of water soluble forms was 0.05–0.1%; the amount of exchangeable forms was 0.2–0.3%.

Protsak and Odintsov [29] have studies speciation of radionuclides in bottom samples collected from the depth of 5–7 m in the northern part of the cooling pond in 2012. The studied bottom sediment samples represented silty sand. Their results are in general agreement with the discussed above data of [16]. The main part of radionuclides (^{137}Cs, ^{90}Sr, ^{241}Am, Pu isotopes) in bottom sediments (> 98%) was found to be in the non-exchangeable ("fixed") form. Interpretations of data of sequential extraction studies lead to conclusion that some 70–80% of ^{90}Sr and ^{241}Am in bottom sediments are associated with the fuel particles.

Autoradiography analyses have shown that the main activity in bottom sediments is associated with the fuel particles with the diameter of ~3 µm and more. About 7% of activity in bottom sediments was found to be associated with the "extra-stable" hot particles, which did not disintegrate even after treatment by the mixture of heated concentrated hydrochloric and nitric acids.

3.2.5. Radionuclide activity ratios in bottom sediments

Important peculiarity of radioactive contamination of cooling pond is that inventory of ^{137}Cs in the pond is approximately 5 times higher compared to the inventory of ^{90}Sr (see TABLE 8).

The above high activity ratio of ^{137}Cs to ^{90}Sr in the pond is contrasting with the radioactive contamination patterns of the surrounding area, where ^{137}Cs to ^{90}Sr activity typically varied in the range of 1:1 to 2:1. It is well known that contamination of the near zone of ChNPP is mainly caused by the so called "fuel component" of the Chernobyl radioactive fallout (i.e. micron-size particles of the nuclear fuel of ChNPP Unit 4 release during the initial explosion and the subsequent fire of the reactor). Activity ratios of different radionuclides in "fuel component" are close to the composition of the nuclear fuel of ChNPP Unit 4 at the time of the accident [35]. Data on typical radionuclide ratios in Chernobyl waste contaminated by fuel particles are listed in TABLE 12.

Activity of ^{90}Sr and transuranic radionuclides in the near-field of ChNPP was initially associated mainly with the radioactive fallout fuel particles. As already discussed, the more volatile ^{137}Cs was released from the damaged Chernobyl reactor mainly in the so called "condensation" component (radionuclide condensate on aerosol carrier particles), which dominates surface contamination patters at larger distance from the ChNPP [35].

TABLE 12. RATIOS BETWEEN THE ACTIVITIES OF RADIONUCLIDES IN THE FUEL-CONTAINING RADIOACTIVE WASTE AT THE CHNPP SITE FOR YEAR 2000 (*based on data* [36])

Radionuclide	Ratio to the activity of ^{137}Cs in %
^{137}Cs	100
^{90}Sr	84
^{238}Pu	0.6
^{239}Pu	0.5
^{240}Pu	0.8
^{241}Pu	48
^{241}Am	1.6

The reason for much higher activity inventory of ^{137}Cs in the pond compared to ^{90}Sr is not fully understood. One possible explanation is the release to the pond of the highly contaminated water from the main contour of the damaged reactor, water used for firefighting etc., which was enriched in ^{137}Cs [26, 27, 37].

The alternative explanation is a hypothetical condensation of the high temperature gaseous activity release from the reactor on the "water vapor curtain", which supposedly existed above the pond at the moment of the accident [6, 29, 33].

One other interesting observation is depletion of ^{90}Sr in comparison to transuranic radionuclides from bottom sediments. Theoretical ^{90}Sr:^{241}Am activity ratio for the fuel of Unit 4 is 28 (for 2012). At the same time, bottom sediments in the cooling pond showed the overall depleted ^{90}Sr:^{241}Am activity ratio of ~ 20 (by 2012), which indicates that about ~30% of ^{90}Sr have migrated outside of the cooling pond system [13, 15].

The estimate of ^{90}Sr depletion from bottom sediments based on radionuclide activity ratio with TRU radionuclides is generally consistent with the independent calculation of ^{90}Sr releases from the cooling pond by groundwater pathway based on groundwater monitoring data [13].

3.3. SURFACE WATER SYSTEM

3.3.1. ^{137}Cs behavior in surface water system

After decay of short-lived radionuclides, radioactive contamination of the water column in the cooling pond was determined mainly by ^{137}Cs and ^{90}Sr (see section 3.1).

Mean ^{137}Cs activity concentration in the water of the cooling pond constituted in summer 1986 according to different sources from 300 to 1000 Bq/L [26, 28]. By 1987 the ^{137}Cs activity concentration decreased to ~ 70 Bq/L. The subsequent dynamics of the mean ^{137}Cs activity concentration in the pond water in 1987–2013 is shown in FIG. 18.

Rapid decrease of ^{137}Cs in the water column of the pond is attributed to sorption to suspended particles followed by sedimentation [6, 26, 20]. Efficient removal of ^{137}Cs from the water column was promoted by high sorption coefficients of ^{137}Cs on suspended particles. Olkhovik et al. [18] estimated the ^{137}Cs Kd for the suspended particles in the cooling pond at ~ 3000 L/Kg.

One other factor causing decrease of radionuclide concentrations in the water of the pond was dilution by large volumes water pumped from Pripyat River to compensate for seepage and evaporation losses (see section 2.1.4). During the post-accident period, the activity concentrations of ^{137}Cs and ^{90}Sr in the water of Pripyat River were always respectively by a factor of about 10 and 50 lower that in the water of the pond [20].

By year 2000, the ^{137}Cs concentration in the pond water has lowered to ~ 2±1 Bq/L, and reached the quasi-steady state with the continued tendency to slow decline. The “ecological half-life” of ^{137}Cs in the water column of the pond for the period of 1998–2010 was estimated at 8.5 years [20].

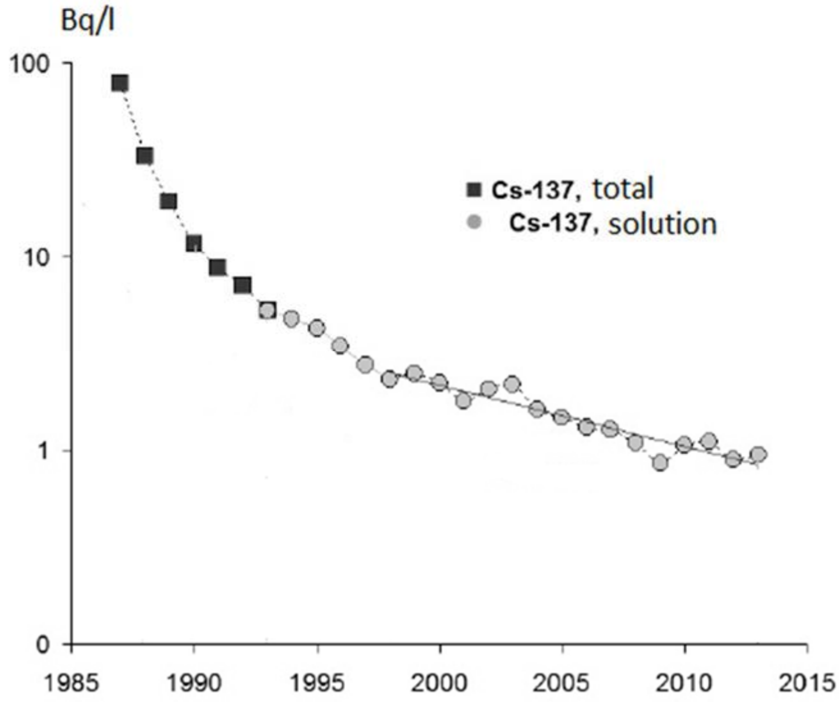


FIG. 18. Yearly averaged ^{137}Cs activity concentration values in the water of the cooling pond in 1987–2013 (data of Ecocenter, Chernobyl, based on data [20]).

Interesting specific feature of ^{137}Cs behavior in the cooling pond was seasonal variation of its activity concentration in the water column (FIG. 19).

The seasonal variation of ^{137}Cs in water column is attributed by several authors [6, 20] to remobilisation of dissolved radiocaesium from the bottom sediments under anoxic conditions in summer months (FIG. 19).

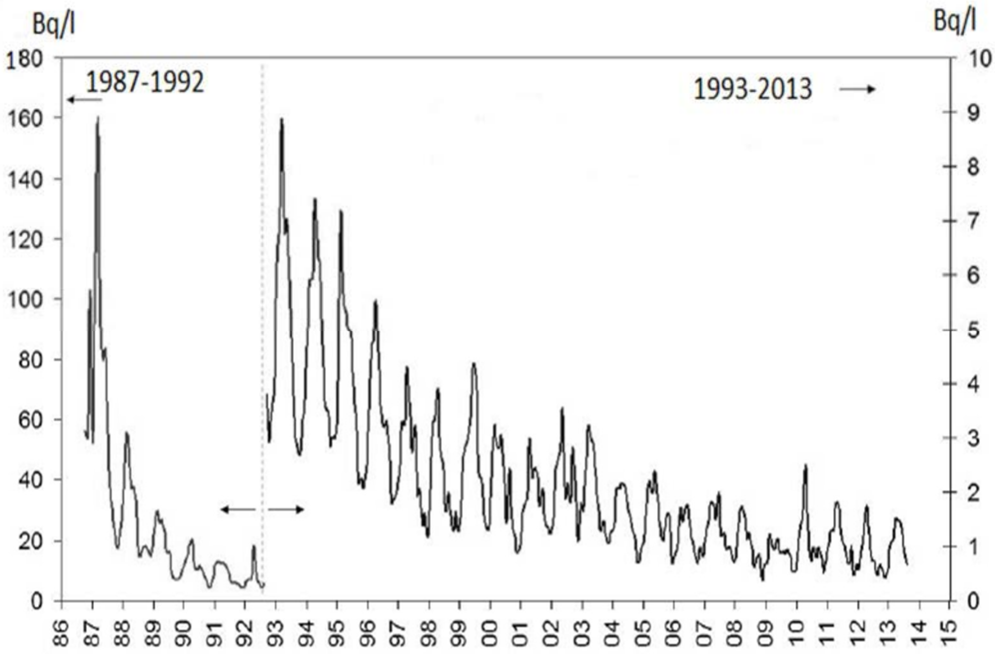


FIG. 19. Monthly ^{137}Cs activity concentration values in the water of the cooling pond in 1986–2013 (data of Ecocenter, Chernobyl) (based on data [20]).

The ^{137}Cs activity pattern appears to be related to seasonal transition between oxic/anoxic conditions at the deep water/sediment interface. Reducing conditions in summer months (due to higher water temperature and intensification of oxidation of organic matter) resulted in increased ammonia-ion concentration in near bottom water layers. Increased NH_4^+ caused remobilization of ^{137}Cs from bottom sediments, as NH_4^+ ions displaced ^{137}Cs from exchange sites in bottom sediments. The discussed above explanation was confirmed by results of monitoring of seasonal changes in vertical profiles of chemical species (dissolved oxygen, ammonia) and ^{137}Cs in the water column of the pond [20].

The described above conceptual model of ^{137}Cs behavior in the cooling pond was also successfully implemented by Dvorzhak et al. [38] using the US EPA water quality computer code WASP6 [39].

3.3.2. ^{90}Sr behavior in surface water system

The behavior of ^{90}Sr in the surface water of the pond differed from that one of ^{137}Cs. It should be reminded that the ^{90}Sr initially entered the cooling pond mainly in the form of nuclear fuel "hot" particles with UO_2 matrix.

The concentration of ^{90}Sr in the water of the pond increased significantly between 1987 and 1988 (i.e. from 7.4 Bq/l to 16 Bq/l) (FIG. 20). This increase may have been caused by release of ^{90}Sr from degrading fuel particles contained in the bottom sediments of the pond [13, 26, 40].

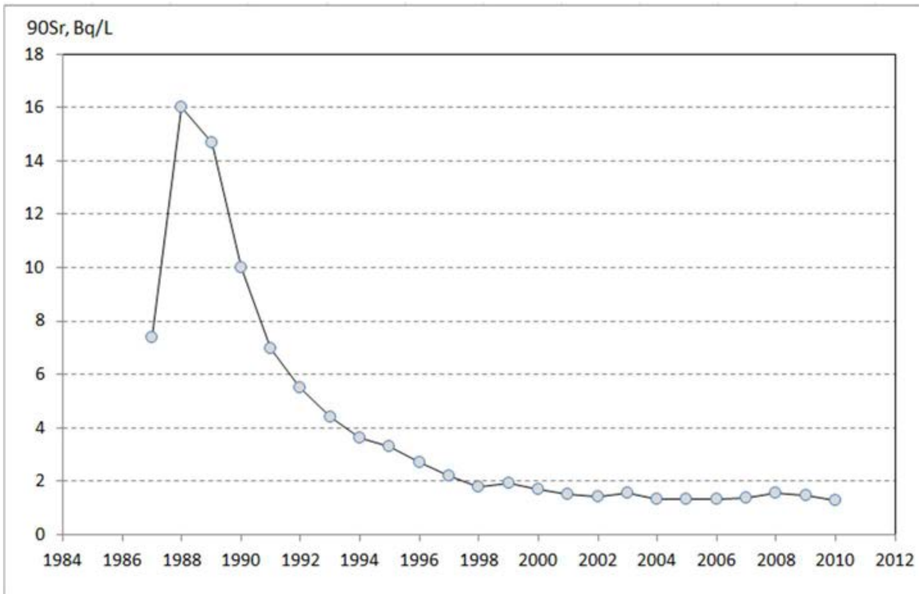


FIG. 20. Yearly averaged ^{90}Sr activity concentration values in the water of the cooling pond in 1987–2011 (based on data of Ecocenter, Chernobyl).

Bugai and Skalskyy [41] carried out ^{90}Sr balance calculations in pond water using monitoring data on ^{90}Sr activity in the water of the pond and in the water of Pripyat River (which was constantly pumped to the pond to compensate for losses), as well as estimates of seepage and evaporation water losses from the pond. This allowed estimating ^{90}Sr input to the pond water presumably caused by dissolution of fuel particles and/or other inputs and exchange mechanisms with bottom sediments (FIG. 21).

Based on balance calculations maximum input of ^{90}Sr to water column was observed during the first years following the accident. In 1987–88 and 1988-89 the estimated input of ^{90}Sr to surface water system of the pond was 2.4×10^9 Bq/year and 1.4×10^9 Bq/year respectively. By 2008 –2010 the ^{90}Sr influx to surface water system decreased to $1–1.5\times10^8$ Bq/year (FIG. 21).

The graph of the ^{90}Sr input (“source-term”) function to the water of the pond (FIG. 21) shows two distinctive exponential trends: “fast” (first ~5 years) and “slow” (subsequent period) components. The described above character of ^{90}Sr leaching from bottom sediments conforms to the model, which assumes presence in Chernobyl accidental radioactive fallout (and respectively in the bottom sediments of the cooling pond) of fuel particles, which were characterized by different dissolution (or weathering) rates [42]: (1) highly oxidized (in the course of reactor fire) and relatively better soluble fuel particles with the uranium oxide matrix, and (2) low oxidized and less soluble fuel particles with the uranium oxide matrix (originating from the initial explosion). In addition, the fallout in the close zone of the ChNPP contained some fraction (~ 10%) of very stable practically non-dissolvable fuel particles with the matrix incorporating the zirconium alloys.

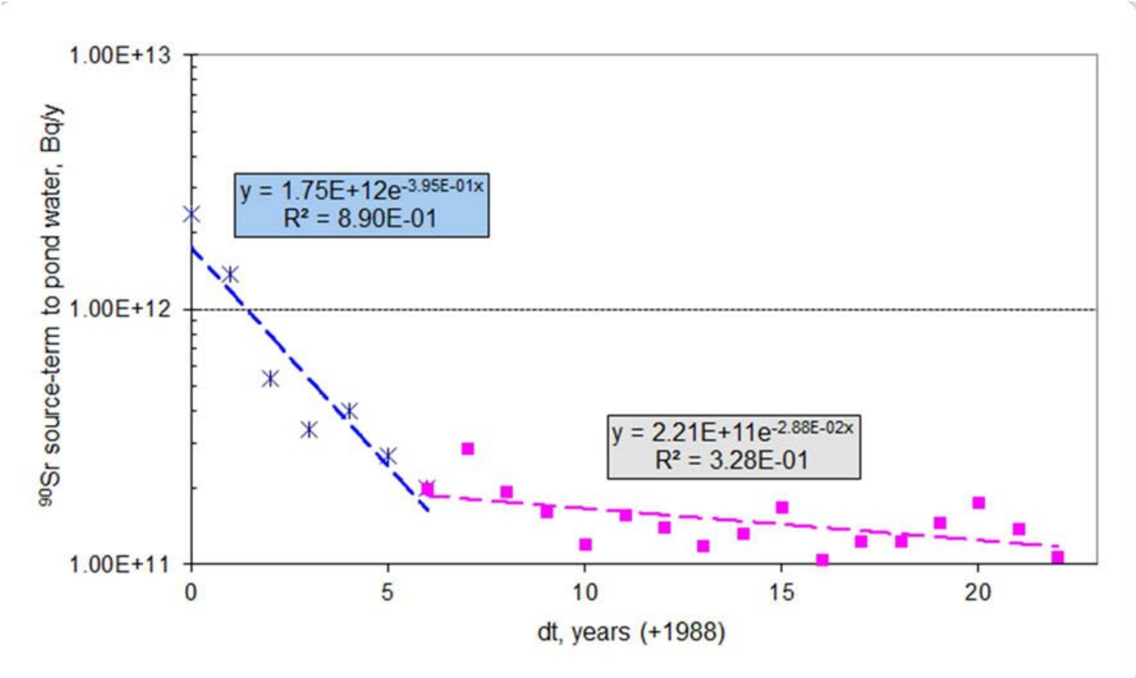


FIG. 21. Estimated ^{90}Sr source-term to cooling pond water column in 1988–2010 (e.g. exchange with bottom sediments) (based on data [41]).

Based on values of coefficients of empirical exponential trends, shown on FIG. 21, dissolution rates of the mentioned above types of fuel particles in the bottom sediments of the cooling pond were estimated at: α_1= 0.4–0.5 year^{-1} ("fast component"), and $\alpha_2\approx$ 0.01 year^{-1} ("slow" component) [41]. These empirical dissolution rate constants are in agreement with data of [42] for the ^{90}Sr release rate from fuel component-contaminated waste material from "Red Forest" waste dump site in Chernobyl zone, which is situated in the close vicinity of the ChNPP and of the cooling pond. It should be noted that studies reported in [29] revealed presence of very stable fuel particles in the bottom sediments of the cooling pond (similarly to "Red Forest" site), which further suggests that both sites were contaminated by similar radioactive fallout fuel particles.

Main mechanism governing the decrease of ^{90}Sr activity concentration in the pond water during the post-accident period (FIG. 20) was dilution by water pumped from Pripyat River. Removal from water due to sorption on suspended particles was a less important mechanism for ^{90}Sr compared to ^{137}Cs due to much smaller sorption distribution coefficients (Kd) values of ^{90}Sr on silt particles. Batch tests on silt sediments from the pond using the ^{85}Sr isotope label resulted in estimated Kd value of 20 ml/g [5].

3.3.3. Radionuclide concentrations in porous solutions of bottom sediments and at the interface" bottom sediments – water column"

Several studies have analyzed radionuclide activity concentrations in the porous solutions of the bottom sediments of the pond [5, 19, 20].

Kanivets et al. [20] have studied in 2002–2003 the vertical distribution of radionuclide activity concentrations in the cooling pond water close to its interface with the bottom sediments (TABLE 13).

These data clearly show that radionuclide concentrations in the near-bottom water layers of the pond were influenced by the elevated radionuclide activity concentrations in porous solutions of bottom sediments.

TABLE 13. VERTICAL DISTRIBUTION OF RADIONUCLIDE ACTIVITY CONCENTRATIONS IN THE SYSTEM 'WATER BOTTOM SEDIMENTS' OF THE COOLING POND IN 2002–2003(*based on data [20]*)

Former «cold» part of the pond, near PK50, depth 6.5 m

Distance from bottom, m	Radionuclide activity, Bq/l							
	October 2002		February 2003		May 2003		August 2003	
	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
5,5	2,8	1,2	1,41	1,25	1,41	0,97	2,5	1,0
2,0	2,8	1,2	2,54	1,43	2,7	1,1	2,0	1,1
0,05	3,2	1,6	NA	NA	NA	NA-	5,5	1,5
-0,05*	2,8	2,4	NA-	2,1	NA	NA	35,0	3,8

Former «warm» part of the pond, near PK216, depth 11.0 m

Distance from bottom, m	Radionuclide activity, Bq/l							
	October 2002		February 2003		May 2003		August 2003	
	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
9,0	2,2	1,2	1,9	1,5	2,35	1,57	3,3	1,3
2,0	2,8	1,2	3,0	1,75	2,0	1,56	3,9	1,8
0,05	4,24	1,86	27,0	2,1	11,2	2,28	6,0	2,8
-0,05*	31,6	7,8	33,3	3,2	33,0	2,2	38,0	4,0

Note: * porous solution from the upper 5 cm layer of bottom sediments

Pirnach [19] has found out that porous solutions of bottom sediments collected from the deep areas of the pond in 2002 contained ^{137}Cs in activity concentrations up to 1117 Bq/L (with mean values of 40–50 Bq/L), while ^{90}Sr activity concentration reached 116 Bq/L (with mean values of ~ 8–10 Bq/L). Maximum radionuclide concentrations in porous solutions were usually located close to the peak of radioactivity in bottom sediment profiles related to the 1986 accident. At the same time ^{137}Cs and ^{90}Sr in surface water of the pond was 0.9 Bq/L and 1.7 Bq/L respectively.

Thus, the cited above studies provided further evidences that bottom sediments may have represented a source of radionuclides to surface water due to diffusive exchange of contaminated pore waters of sediments with the water in the pond.

Kanivets et al. [20] have made further hypotheses that the water body of the pond is contaminated by ^{137}Cs mainly due to diffusive exchange with the silt sediments in the deep areas of the pond. On the contrary, based on observations, the ^{90}Sr activity concentrations in pond water typically were higher in shallow areas compared to the deep areas. This suggests that the ^{90}Sr source in bottom sediments has been likely located in shallow areas (e.g. fuel particles in bottom sediments in shallow areas, where better oxygenated conditions promoted their dissolution and subsequent radionuclide release from the UO_2 matrix to the water column of the pond).

3.4. GROUNDWATER SYSTEM

3.4.1. General characteristic of groundwater migration process from the pond

Contaminated by radionuclides surface water of the cooling pond and porous solutions of the bottom sediments represented the source of groundwater contamination in the vicinity of the cooling pond, and also the source of radioactivity releases via groundwater pathway to the adjacent Pripyat River.

In particular, radionuclides from the pond infiltrated to the unconfined aquifer in Quaternary alluvial sandy deposits in between the cooling pond and Pripyat River (FIG. 3). The seepage from the cooling pond further ex-filtrated to the drainage ditches, while part of ground water flow was directed in subsurface to the Pripyat River (FIG. 3 and FIG. 4).

3.4.1.1. Hydraulic parameters of geological deposits at the cooling pond site

To analyze and interpret data on radionuclide migration to groundwater it is important to know information about hydraulic properties of the soils of the dam and geological deposits at the cooling pond site. This information is also needed to parameterize groundwater flow and radionuclide transport models of the cooling pond. Comprehensive programme of experimental hydrogeological characterization studies of the cooling pond was carried out in 1999–2001 [13]. This programme included laboratory column tests on drill core samples from the cooling pond dam, field hydraulic slug tests on wells, and single well tracer dilution tests. Tracer experiments were completed at 4 locations of the cooling pond dam inbetween the cooling pond and Pripyat River (at PK-64, PK-104, PK-113 and PK-121). At each site, tests were carried out in wells sampling 2–3 depth intervals (from 7 to 20 m) in the unconfined aquifer in Quaternary deposits. The experiments consisted in introducing to the well of tracer (rodamine), and subsequent measuring of the evolution (decrease) of tracer concentration in time inside the well due to dilution by horizontal groundwater flow passing through the well screen. The derived in such a way curves of tracer concentration decrease in wells allowed estimating of groundwater flow pore velocity using relevant theoretical equation [43]. Results of tracer experiments are summarized in TABLE 14.

Tracer test data for well 9P disagree with data for other wells, and with slug test data. This may have been caused by vertical (rather than horizontal) flux in well shaft caused by stratified structure of deposits and resulting hydraulic head gradient between different sublayers. Therefore, data from well 9P were not used for calculating mean estimates of hydraulic parameters listed in TABLE 14.

The tracer tests provided the mean pore water flow velocity values in the unconfined aquifer in Quaternary alluvial deposits between the cooling pond and Pripyat River in the range 0.32–0.64 m/day, and the corresponding mean values of hydraulic conductivity in the range from 4.2 to 8.4 m/day. These data are in reasonable agreement with results of the slug-tests, which have provided mean values of hydraulic conductivity of K=4.5 m/day (see TABLE 14). The laboratory column tests have given the mean hydraulic conductivity value of K=6.5 m/day, which generally agree with the results of field tests.

3.4.1.2. Mobility of radionuclides from Chernobyl accidental release in groundwater

The most mobile radionuclide in groundwater in the zone of influence of the cooling pond was ^{90}Sr [11, 13, 21]. Maximal activity concentration of ^{90}Sr in groundwater at the northern perimeter of the pond dam (PK-14) reached 81 Bq/L in 1999 [4], which by a factor of ~40 exceeded the Ukrainian drinking water standard for ^{90}Sr of 2 Bq/L [44].

TABLE 14. RESULTS OF TRACER TESTS IN THE UNCONFINED AQUIFER IN-BETWEEN THE COOLING POND AND PRIPYAT RIVER (*based on data* [13])

Location	Well no.	Depth interval, m	Tracer experiments		Slug-tests
			V_{real}, m/day*	K, m/day**	K, m/day**
PK-64	7P	6.6–7.6	0.23–0.46	4.6–9.2	2.6
	9P ***	12.4–13.4	2.2–4.4	44.0–88.0	0.8
PK-104	2	17.0–18.0	0.47–0.94	4.7–9.4	4.1
	2A	12.2–13.7	0.13–0.26	1.3–2.6	3.2
	2B	9.0–10.5	0.7–0.14	7.0–14.0	5.8
PK-113	3P1	6.0–7.0	0.26–0.52	3.1–6.2	4.2
	3P2	15.8–16.8	0.08–0.16	1.0–1.9	2.0
	3P3	18.4–19.4	0.35–0.7	4.2–8.4	4.0
PK-121	121/3	5.6–6.6	0.34–0.68	7.7	9.9*
Mean (without well 9P)	NA	NA	0.32–0.64	4.2 – 8.4	4.5

Notes: * estimated groundwater flow velocity; ** estimated hydraulic conductivity; *** data for well 9P are not included to the calculations of mean parameter estimates from tracer tests.

Activity concentration of ^{137}Cs in groundwater during the post-accident period was of an order of 0.01–0.1 Bq/L or less, while the activity of sum of ^{239}Pu and ^{240}Pu was 0.001 Bq/L or less [4, 41]. The above values are several orders of magnitude below the drinking water standards for these radionuclides. This is explained by much higher sorption and retardation of ^{137}Cs and Pu isotopes (compared to ^{90}Sr) by soils of the dam and of the aquifer.

Therefore, the ^{90}Sr migration from the cooling pond to groundwater and to the adjacent Pripyat River was of primary concern, while other radionuclides were effectively retarded by local geological barriers.

3.4.1.3. *Role of bottom sediments in groundwater contamination*

Monitoring data suggest that bottom sediments of the cooling pond evidently played essential role not only in contaminated of the surface water system of the pond (see section 0), but also in contamination of the groundwater.

Maximum ^{90}Sr concentrations in groundwater in the northern part of the pond (i.e. 81 Bq/L at PK-14 in 1999 [4]) were higher than maximum concentrations in the surface water of the pond during the whole observation period (i.e. 16 Bq/L in 1988; see Section 3.3.2).

Similar picture was observed at PK-113 of the cooling pond dam, where ^{90}Sr in groundwater reached 30–35 Bq/L in 1989. The reported elevated ^{90}Sr concentrations in groundwater (compared to surface water) are of the same order of magnitude as contamination levels observed in porous solutions of bottom sediments (See Section 0).

Elevated concentrations of ^{90}Sr in groundwater are likely caused by additional leaching of radionuclide to pore waters from fuel particles contained in bottom sediments during seepage through the "bottom sediment – aquifer" interface zone [13, 40].

3.4.1.4. *Specifics of hydrodynamics of water filtration from the pond*

To interpret results of groundwater monitoring, it is important to understand peculiarities of groundwater flow process from the pond.

The hydrodynamic flow network in the aquifer cross-section between the cooling pond and Pripyat River obtained by means of groundwater modeling using Modflow [45] code is shown in FIG. 22. This model corresponds to the conditions (e.g. subsurface system geometry etc.) of the PK-113 of the dam of the pond.

Based on modeling results about 78% of seepage from the pond is intercepted by the drainage ditch, while about 22% of seepage goes directly to Pripyat River.

The groundwater travel time from the cooling pond to the drainage ditch was estimated at 2–3 months (for the different path-lines). Direct groundwater seepage from the pond in the unconfined aquifer to Pripyat River took 1.5–3 years, while seepage through the confined aquifer in Eocene deposits took 30 years and more.

Calculated graph of the distribution of the vertical water flow velocity through the pond bottom at different distances from the shoreline of the pond (point x=0) based on groundwater modeling is shown in FIG. 23. This graphs shows that the intensive flow through pond bottom occured only within the limited 30–40 m horizontal interval from the shore line of the pond. At the larger distances the rate of infiltration flux through the pond water droped to very low values. Therefore leaching of radionuclides from bottom sediments to groundwater was possible only in the zone of bottom near to the shoreline, while bottom sediments in deeper areas of the pond were not involved actively to geo-migration process.

It should be pointed out that in some locations of the cooling pond dam (e.g. PK-14 – PK-27) distance between the cooling pond and Pripyat River increases to 350 – 500 m (which is by a factor of 1.5–2 more than at PK-113). Therefore, groundwater velocities in such locations were proportionally lower, leading to increase in groundwater travel times from the pond to Pripyat River to 3–5 years.

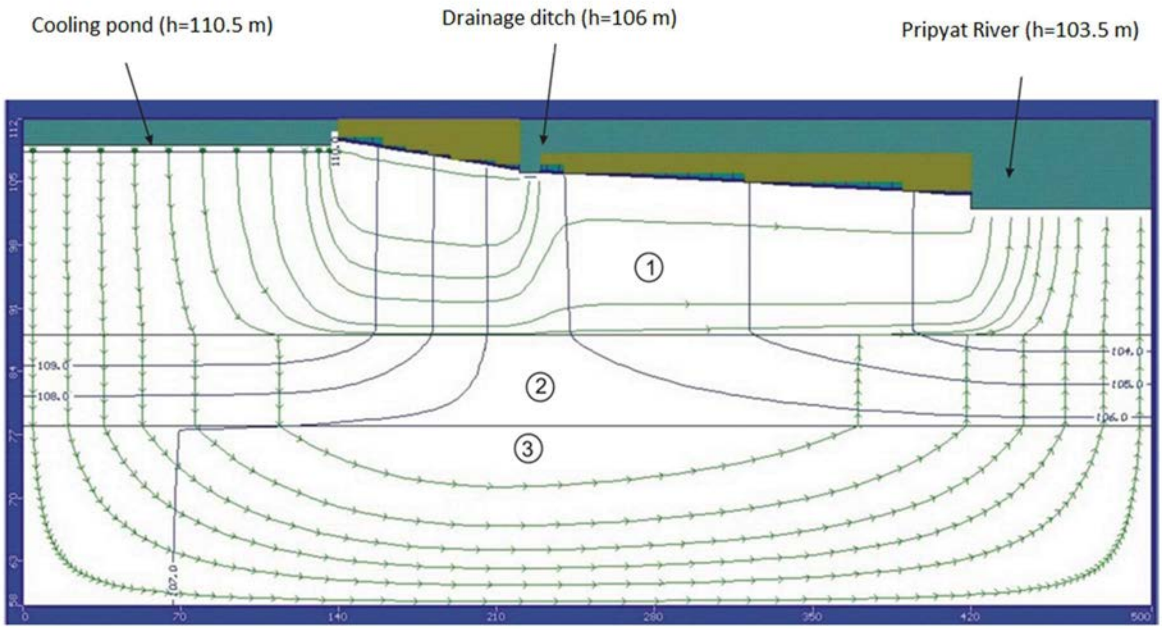


FIG. 22. Scheme of 2D groundwater flow in the aquifer cross-section (lines of constant head and flow path-lines) in the system "cooling pond – drainage ditch – Pripyat River". Distance between arrows corresponds to groundwater travel time of 1 year. Notation: (1) unconfined aquifer in Quaternary alluvial sandy deposits (K_f=10 m/day); (2) Eocene marl aquitard layer (K_f=0.005 m/day); (3) confined aquifer in the Eocene sandy deposits (K_f=5 m/day) (based on data [41]).

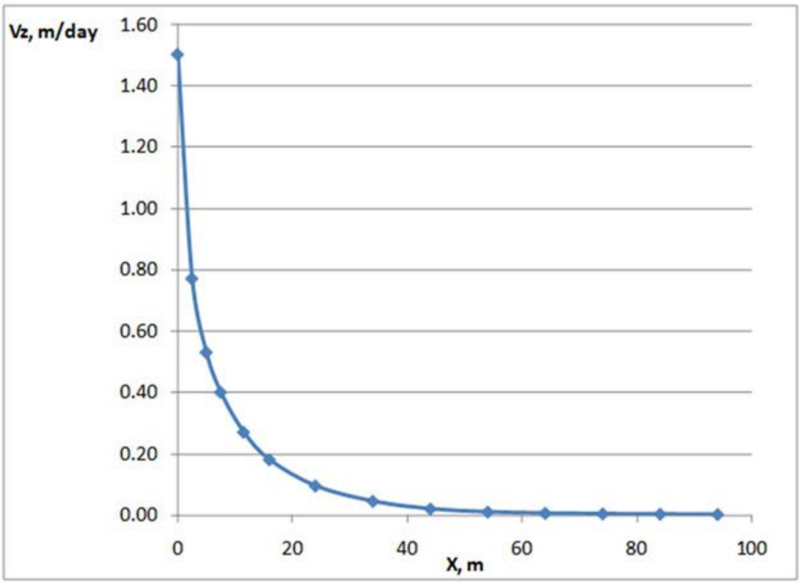


FIG. 23. Distribution of the vertical water flow velocity through the pond bottom at different distances from the shoreline (point x=0) based on groundwater modeling, based on data [41].

3.4.2. Specifics of groundwater contamination at different locations of the pond perimeter

3.4.2.1. Groundwater monitoring system

Groundwater monitoring observations at the cooling pond site were carried out during the post-accident period by the monitoring service of the Chernobyl Exclusion Zone.

The groundwater monitoring observations were carried out on individual wells and multilevel well profiles installed at several locations of the cooling pond dam (at PK-14, PK-32, PK-64, PK-104, PK-113 and PK-121) (FIG. 2). At some of these locations (PK-14, PK-113) clusters of multi-level 7–20 m deep wells to the unconfined aquifer were installed at different distances from the pond forming monitoring well profiles oriented towards the Pripyat River.

Detailed description of the monitoring system with technical characteristics of wells is provided in [4].

3.4.2.2. Contamination of groundwater in the aquifer between the cooling pond and Pripyat River

Typical time series of the ^{90}Sr activity concentration in groundwater at different locations of the dam between the cooling pond and Pripyat River are shown in FIG. 24 and FIG. 25.

At the segment of the dam along the Pripyat River from PK-32 to PK-127 maximum concentrations of ^{90}Sr in groundwater (up to 20 Bq/L) were observed for different wells during the period from 1991–1995 (see FIG. 24).

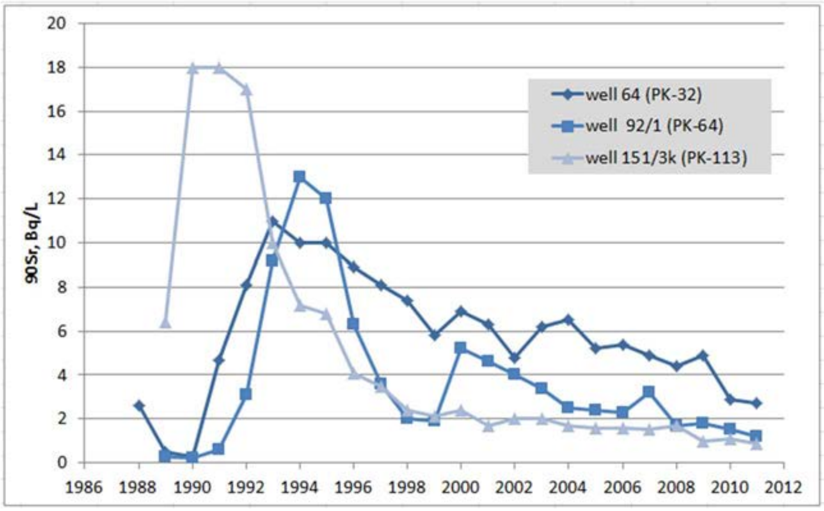


FIG. 24. Groundwater contamination by ^{90}Sr at PK-32, PK-64 and PK-113 of the cooling pond dam in 1988–2011 (based on data of the Ecocenter, Chernobyl).

During the subsequent period, a decrease in ^{90}Sr in groundwater was observed caused by decrease of ^{90}Sr activity in the source of radionuclide migration-surface water of the cooling pond. Observed variability in the peak values and arrival times of ^{90}Sr to different wells can be explained by different depth of individual wells, and by variability of hydraulic and sorption properties of aquifer sediments for different locations.

By 2010 the activity concentrations of ^{90}Sr in groundwater in the discussed locations varied in the range from 0.9 to 3.2 Bq/L, which was close to contamination of surface water in the cooling pond.

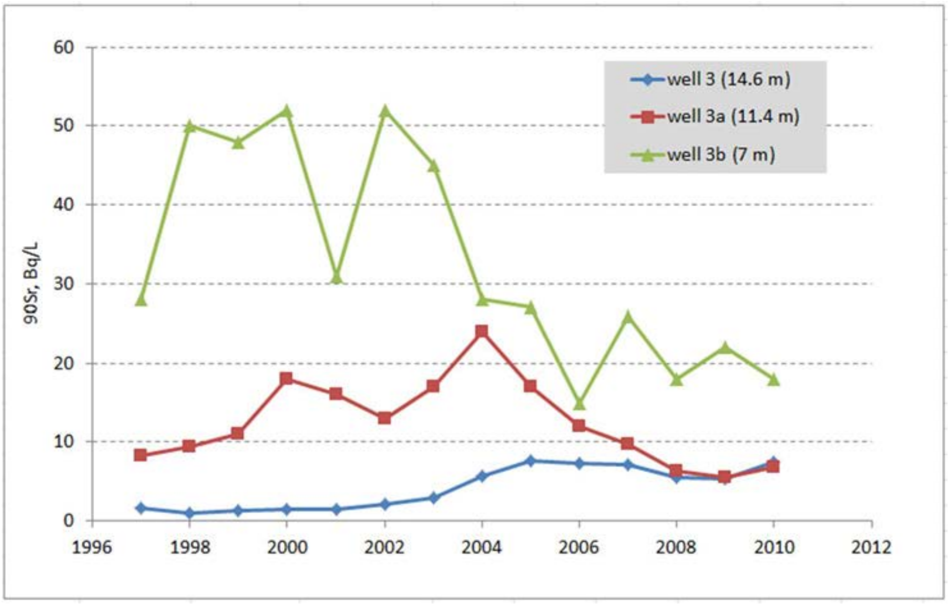


FIG. 25. Groundwater contamination by ^{90}Sr at PK-14 of the cooling pond dam in 1997–2011 (based on data of the Ecocenter, Chernobyl).

Activity concentrations of ^{90}Sr in groundwater in the northern part of the cooling pond (PK-14) were noticeably higher compared to PK-32 and PK-113 (FIG. 25). Here activity concentration of ^{90}Sr in well no.3b reached 50–52 Bq/L in 1999–2002. Higher groundwater contamination levels in this area are likely related to higher bottom contamination densities by ^{90}Sr in the northern part of the pond, and respectively higher leaching rates of radioactivity to groundwater from the bottom sediments. Later arrival of peak ^{90}Sr concentrations to wells is explained by lower groundwater flow velocities in this area (as in this location cooling pond is separated from the Pripyat River by a wider strip of land). In accordance with the general hydrodynamic patterns of water seepage from the pond to Pripyat River (see Section 3.4.1.4) monitoring well sampling the upper part of the aquifer (well no.3b) was characterized by earlier arrival time and by higher values of ^{90}Sr activity concentration in groundwater.

3.4.2.3. Contamination of seepage water in drainage ditches

Data on contamination by ^{90}Sr of the water of Northern and Southern drainage ditches of the cooling pond are shown in FIG. 26.

The time dynamics of ^{90}Sr activity concentration in the water of drainage ditches followed the general trend for ^{90}Sr concentration in the cooling pond. Activity concentration of ^{90}Sr in the water of drainage ditches was somewhat higher than in the cooling pond. This can be explained by retardation of ^{90}Sr in the course of groundwater seepage through the dam.

Somewhat elevated ^{90}Sr concentrations in the water of the Southern drainage ditch can be explained by additional radionuclide leaching from the contaminated bottom sediment “hot spot” situated at the mouth of the outflow channel of the pond.

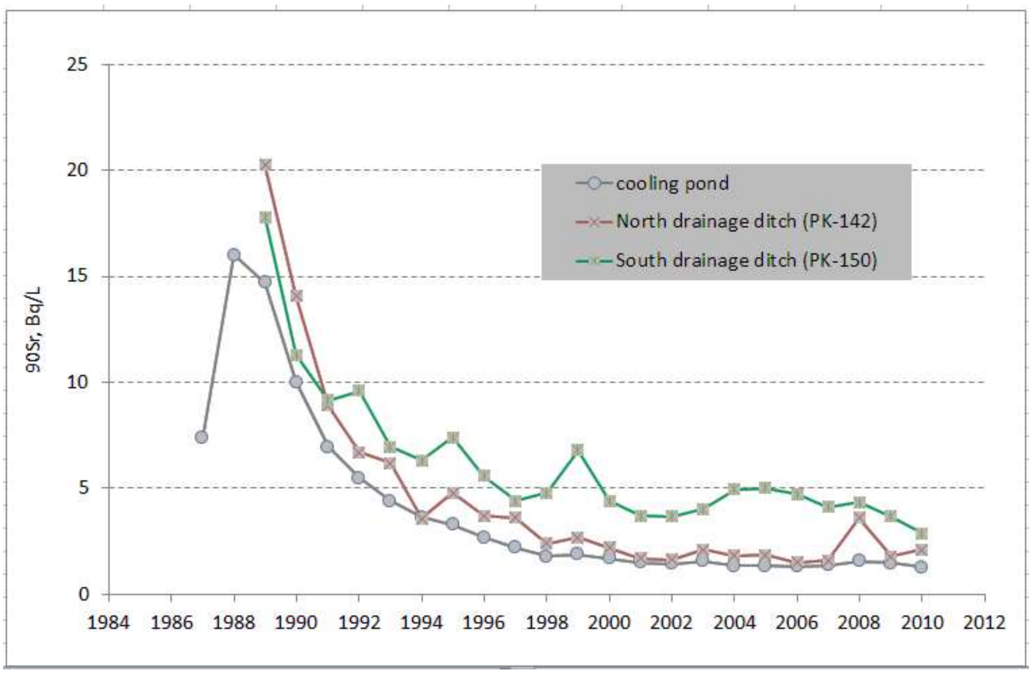


FIG. 26. Contamination by ^{90}Sr of the drainage ditches of the cooling pond in 1987–2011 (based on data of Ecocenter, Chernobyl).

3.4.3. Sorption properties of soils of the cooling pond dam

Available groundwater monitoring data in wells located between the cooling pond and Pripyat River allowed estimation of ^{90}Sr retardation factors and sorption distribution coefficients of aquifer soils based on analyses of ^{90}Sr breakthrough curves in monitoring wells [13]. Respective estimates are presented in TABLE 15.

Groundwater travel times to wells (non-retarded) were estimated using the MODFLOW-based groundwater flow model of the cooling pond (FIG. 22).

Estimates of ^{90}Sr Kd-s for different wells and locations (PK-64, PK-113) are in good agreement. Mean value of retardation coefficient for ^{90}Sr is R=5.5, while the mean Kd is ≈ 1 l/kg. These estimates correspond to the low end values of ^{90}Sr sorption parameters for soils reported in literature [46]. Low sorption parameters are caused by lithological composition and mineralogical composition of local alluvial sediments (medium quartz sands, see section 2.2.2.2), and also by relatively high Ca concentration in water of the pond (i.e. 30–50 mg/l), which competes for ^{90}Sr for exchange sites on soil matrix.

Taking into account retardation due to sorption, time of ^{90}Sr migration from the pond to drainage ditches is estimated 1–2 years. Time for ^{90}Sr subsurface transport to Pripyat River for different locations of the dam of the cooling pond is estimated from 8–12 years (PK-32 and PK-127) to 16–20 years (PK-14 and PK-20) [13].

TABLE 15. ESTIMATES OF RETARDATION AND SORPTION PARAMETERS OF ^{90}SR BASED ON DATA OF OBSERVATIONS OF RADIOACTIVE CONTAMINATION OF GROUNDWATER BETWEEN THE POND AND PRIPYAT RIVER (*based on data of [13]*)

Well	Date of max. ^{90}Sr concentration in well (mm/yy)	Time of migration ^{90}Sr, months	Distance to pond, m	Ground water travel time*, months	Retardation coefficient (R)	Kd, ml/g
PK-113						
no. 151/1-1/k	03/89	35	90	4	8,6	1,3
no. 151/2-2/k	03/89	35	150	9	3,8	0,5
no. 151/3-3/k	09/90	53	200	13	4,1	0,5
no. 151/4k	01/92	69	260	16	4,3	0,6
PK-64						
no. 92/1	06/93	86	200	13	6,6	1,0
no. 92/2	01/94	93	240	17	5,5	0,8
Mean					5,5	0,8
Minimum.					3,8	0,5

Note: * modeling estimate

Sequential extraction studies of on contaminated sandy deposits from the aquifer between the cooling pond and Pripyat River has shown that about 90% of ^{90}Sr is in ion-exchangeable form (i.e. can be extracted by 0.1M $CaCl_2$) solution [47].

In situ “soil – porous solution” partition tests on deposits samples from the contaminated aquifer have yielded ^{90}Sr Kd values of 3–7 ml/g [48]. These values are noticeably higher than those back-calculated from the ^{90}Sr plume velocity (see TABLE 15). This can be the result of a partly non-exchangeable ^{90}Sr sorption process: some of radionuclide which was adsorbed on soil from a historically higher-concentration solution (during an early phase of migration from the pond) was retained on deposits, which resulted in a higher values of “apparent” in-situ ^{90}Sr Kd-s [11].

Based on data of [18] ^{137}Cs Kd for soils of the dam is estimated at 150–300 l/kg, which correspond to the retardation factor R= 800–1600. This shows that the ^{137}Cs was essentially immobile in subsurface environment.

3.5. RADIOACTIVE CONTAMINATION OF PRIPYAT RIVER DUE TO SEEPAGE FROM THE POND AND RELATED REMEDIAL MEASURES

3.5.1. Radioactivity fluxes from the pond to the Pripyat River

The cooling pond represented during the post-accident period one of important sources in Chernobyl zone of the ^{90}Sr migration to Pripyat River. However the potential risks of contamination of Pripyat River by radioactivity from the cooling pond were significantly overestimated in the early aftermath of the Chernobyl accident leading to unjustified, costly and inefficient remedial measures. The issue of remedial measures will be discussed in more detail in the next paragraph.

Estimates of integral releases of ^{90}Sr by groundwater pathway from the cooling pond to Pripyat River (including discharges from drainage ditches are subsurface transport) during the period from 1989 to 2010 are shown in FIG. 27.

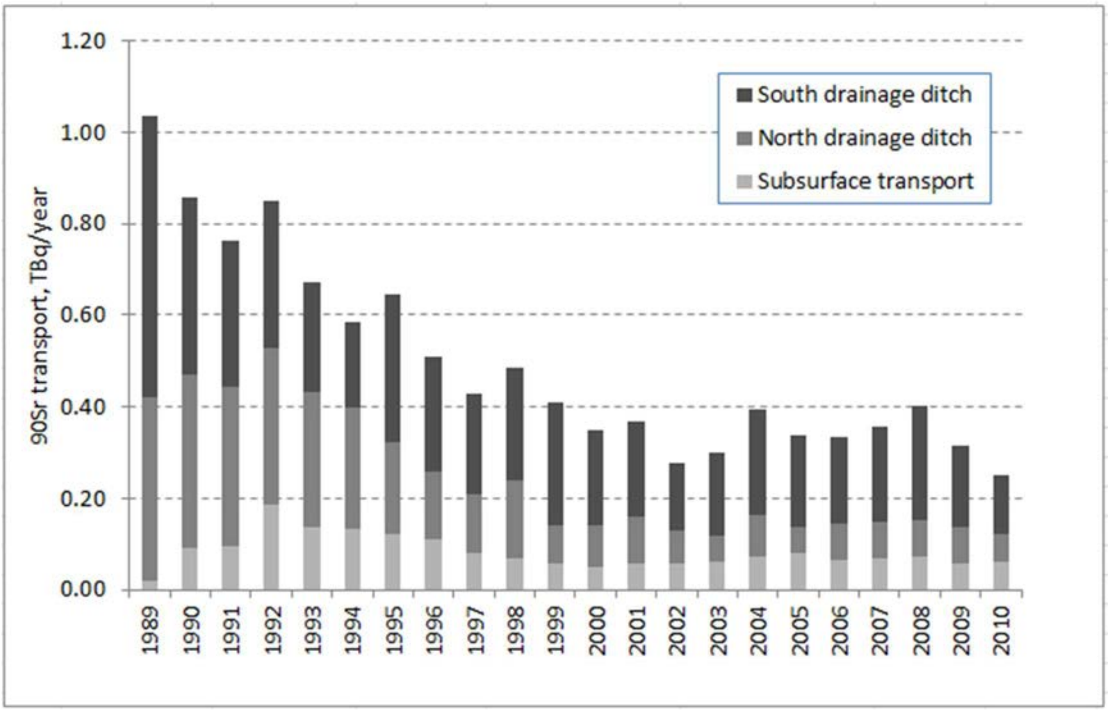


FIG. 27. Transport by groundwater pathway of ^{90}Sr from the cooling pond to Pripyat River in 1989–2010 (based on data of [41]).

Data on ^{90}Sr releases with the drainage water are based on monitoring observations of the Ecocenter (Chernobyl) on water discharge rates and radionuclide activity concentrations in drainage ditches of the pond.

The ^{90}Sr transport from the pond in the subsurface groundwater flow was estimated based on monitoring data on ^{90}Sr activity concentrations in monitoring wells, and using measured groundwater flow velocities in the aquifer between the cooling pond and Pripyat River. Groundwater velocities in the aquifer were measured in the course of the single-hole tracer dilution tests, which provided average velocity values of 0.32–0.64 m/day (see Section 3.4.1.1). The upper bound estimate of flow velocity (0.64 m/day) was used in calculation of ^{90}Sr releases from the pond.

From 1989 to 2010 the ^{90}Sr releases from the cooling pond to Pripyat River have decreased by a factor of about four (from ≈1 to 0.26 TBq/year), with the continued descending trend. It can be seen that the main release pathway was seepage of the contaminated groundwater to the drainage ditches, while the subsurface pathway was of less significance in the integral ^{90}Sr transport from the pond.

During the post-accident period, the cooling pond contributed from 5% (e.g. 1991 and 1993) to 22% (in 1992) to the overall transport of ^{90}Sr by Pripyat River to the downstream Dnieper River system (depending on hydrological conditions of particular year and contributions from other sources, such as contaminated floodplain soils during the spring flood events etc.). In 2010 releases from the pond accounted for ~10% of ^{90}Sr transport by Pripyat River [11, 41].

3.5.2. Groundwater remediation history

The ChNPP is located in the headwater drainage area of the Pripyat – Dnieper River system, therefore the potential threat from the hydrological transport of radionuclides to the downstream population centers(including Kiev) was one of major concerns from the first days following the Chernobyl accident.

Almost immediately after the Chernobyl accident the Government of the Soviet Union initiated a large scale engineering measures to protect the Dnieper River system from the secondary contamination by the Chernobyl fallout radionuclides, which included construction of “sediment traps” on rivers, zeolite containing “filtering dykes” on streams and small rivers, and also installing several drainage well “curtains” and a slurry wall barrier around ChNPP to isolate Pripyat River from the contaminated groundwater [11, 49, 50].

As a part of the listed emergency response measures, a drainage curtain was constructed in between the cooling pond and Pripyat River in order to protect the river from the seepage of radioactively contaminated water from the pond (FIG. 28A). The drainage curtain was 13.5 km long, and it included 177 pump wells to the Quaternary alluvial aquifer (20 m deep; 240 mm diameter). The project design integral pumping rate of the drainage curtain was 103×10^6 m^3/year. As the technology to treat such a large volume of radioactively contaminated water has not been available yet, it was planned (as an interim measure) to return the pumped water to the cooling pond. In parallel, the R&D work to develop technologies to treat large volumes of contaminated water was initiated. However, because no serious groundwater contamination at the cooling pond has been revealed by the end of 1986, the drainage curtain was put on reserve.

In 1988–1989 mobility of the ^{90}Sr in the cooling pond surface water and groundwater system has increased due to dissolution of fuel particles in the bottom sediments of the pond (see Sections 3.3, 3.4). Therefore, new remedial analyses were initiated in 1989–90 to address the problem, and evaluate the necessity to put the drainage curtain into operation [12]. The new analyses have identified serious shortcomings of the engineering design of the drainage curtain. Modeling analyses has shown that about 30% of the debit of drainage water will be formed by water seeping from the Pripyat River (FIG. 28A). This additional volume of water pumped to the pond may be larger than evaporation losses from the pond. Other potential negative consequences included predicted increase of dissolved salts concentrations in the surface water system of the pond "sealed" by drainage curtain, as well as intensification of radionuclide migration from the bottom sediments in the deeper areas of the pond. In view of these risks and concerns, the drainage curtain has never been put into operation [11, 50].

As an alternative protective system, an "open channel" drainage system construction between the cooling and Pripyat River was started in 1991 (FIG. 28B). In addition to preventing seepage from the pond to Pripyat River, this system was supposed to collect drainage water from the North Drainage ditch, and return intercepted water to the pond using pumping stations installed along the drainage contour perimeter. As remedial funds were limited, the bottom and sides of the opened drainage channel has not been properly reinforced. During next several years, erosion of the constructed channel rendered this system to the non-working condition. As repair and maintenance costs for the open channel drainage system were high, it either was never put to operation.

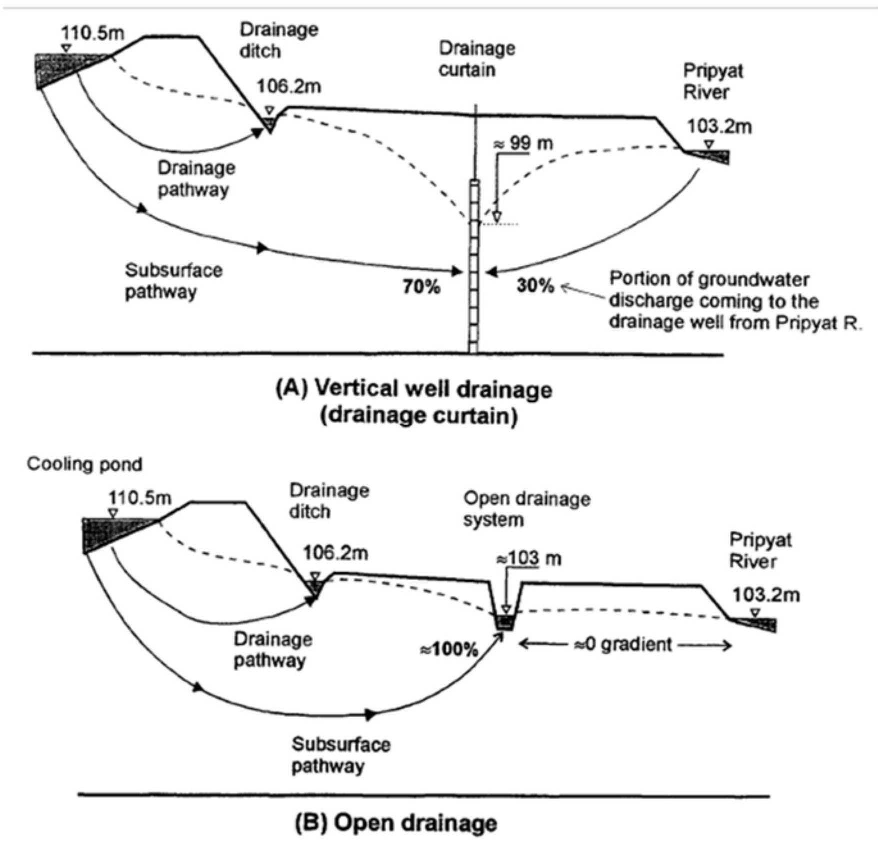


FIG. 28. Engineered "hydraulic barrier" system designs to capture the seepage of the contaminated groundwater from the pond, based on data [50].

Retrospective analyses of the described above remedial efforts have identified a number of strategic mistakes of the remedial designs [11, 50]:

- Initiation of remedial works at ChNPP site just 1 month after the accident in conditions of high worker exposure was not justified, as radionuclide migration to groundwater was a relatively slow process due to sorption and retardation on aquifer sediments; reserve of time existed for implementing (if necessary) protective designs in less acute radiation conditions;

- Both drainage curtain and open channel system were aimed at mitigating of the subsurface migration pathway to Pripyat River. However, the subsequent more accurate assessments have shown that this pathway is of minor importance compared to direct discharges of drainage water from the drainage ditches of the pond (see Section 3.5.1.); this miscalculation was the result of the lack of good understanding of the hydrogeological system of the cooling pond;

- In the early remedial analyses the remediation criteria for the cooling pond usually refer to drinking water standards without site specific dose assessment analyses. Later dose assessments [51] have shown that ^{90}Sr releases from the pond to Pripyat River only marginally contribute to exposure of the downstream population, which is dominated by other pathways and activity sources; while the doses due to hydrologic transport even for critical groups (such as fishermen at Kievskoe Reservoir at Dnieper River) were in 1990s well below the reference level of 1 mSv/year.

3.6. CONTAMINATION OF AQUATIC BIOTA

The Chernobyl cooling pond was a highly productive aquatic ecosystem inhabitated by the diversity of higher aquatic plants, phyto and zooplankton, phyto and zooperiphyton, zoobenthos and fish (see Appendix III). Following the Chernobyl accident, the cooling pond was one of the most contaminated water reservoirs in the Chernobyl exclusion zone. High levels of contamination of water and bottom sediments of the cooling pond resulted in radioactive contamination of the aquatic habitat of the pond.

The main attention in studies of radioactive contamination of biota during the post-accident period was paid to macrophytes (higher aquatic plants and large algae), mollusks and fish. Data on radioactive contamination of aquatic biota in the cooling pond presented below are mostly based on the review of the subject carried out by IHB [25] for the feasibility study of Chernobyl cooling pond decommissioning.

3.6.1. Higher aquatic plants

Systematic radioecological monitoring studies of the aquatic species of the cooling pond are carried out since early 1990s [52–54].

The ^{137}Cs activity in the dominant species of the higher aquatic plans in the cooling pond has generally shown significant decrease in 1993–2013. For *Ceratophyllum demersum* the activity has decreased from 1500 to 500–600 Bq/kg; for *Myriophyllum spicatum* the activity has decreased from 5000 to 2500 Bq/kg. The observed decrease of radionuclide activity in plants generally correlates with the decrease of ^{137}Cs in the water of the pond, which has decreased from 1990s by a factor of about 3 (see Section 3.3.1). Example dynamics of ^{137}Cs activity in *Ceratophyllum demersum* in 1998–2013 is shown in FIG. 29.

The ^{90}Sr activity in the higher aquatic plants during the same period has shown relative stability. For *Ceratophyllum demersum* the ^{90}Sr activity varied in the range 100–150 Bq/kg; for *Myriophyllum spicatum* 200–250 Bq/kg; for *Phragmites australis* 500–800 Bq/kg. Example dynamics of ^{90}Sr activity in *Ceratophyllum demersum* in 1998–2013 is shown in FIG. 30.

3.6.2. Mollusks

Bivalve mollusks dominate by mass group of aquatic species in the cooling pond. The shell constitutes 50–70% of mass of the mollusk. It is composed from calcium carbonate, and intensively accumulates ^{90}Sr, which is a chemical analog of Ca. Data on mollusk radioactivity in the pond are illustrated below using data for *Dreissena*, which is the dominant mollusc species in the cooling pond. Data of [25, 55] on ^{137}Cs in soft tissues of *Dreissena* in the cooling pond in 1986–1999 show rather rapid decrease of radionuclide content in the mollusc during first years following the accident, with stabilization in the later years (FIG. 31).

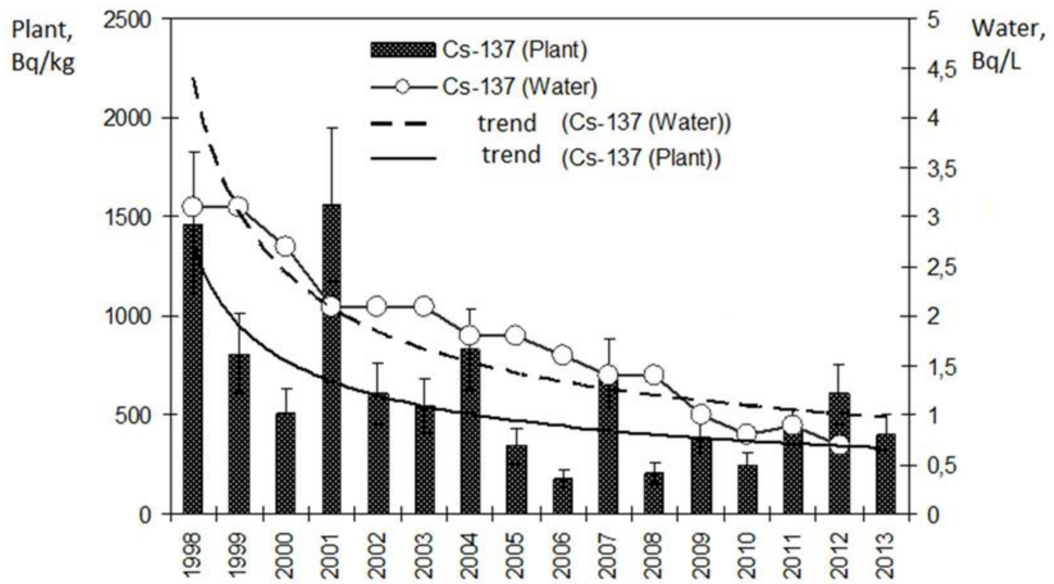


FIG. 29. Time dynamics of ^{137}Cs activity in Ceratophyllum demersum in the former "cold zone" of the cooling pond in 1998–2013 (based on data of [25])

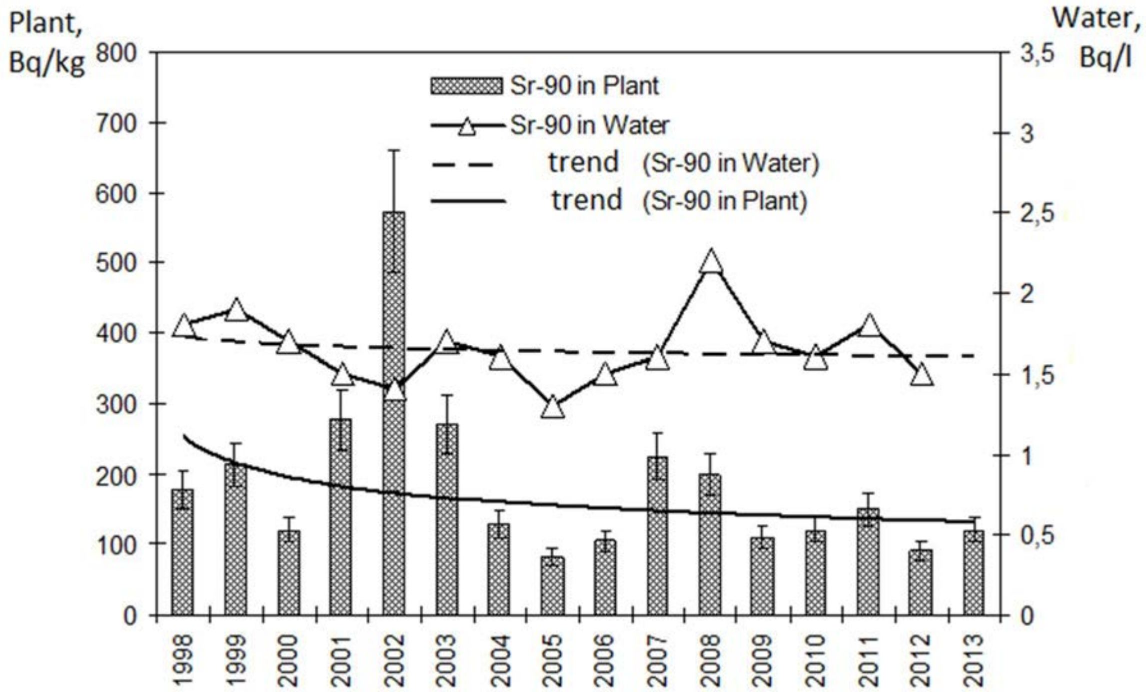


FIG. 30. Time dynamics of ^{90}*Sr activity in* Myriophyllum spicatum *in the former "cold zone" of the cooling pond in 1998–2013 (based on data of [25]).*

Data on dynamics of specific activity of ^{90}Sr and ^{137}Cs in *Dreissena* during the 17 year period (1996–2013) based on studies of [54, 56, 57] show fluctuations with a tendency to decrease of specific activity during the observation period (by a factor of up to 2) (FIG. 32). The ^{137}Cs activity decreased from ~1000–1500 Bq/kg to ~ 500 – 1000 Bq/kg, while the ^{90}Sr activity decreased from ~2000 Bq/kg to ~ 1000 Bq/kg.

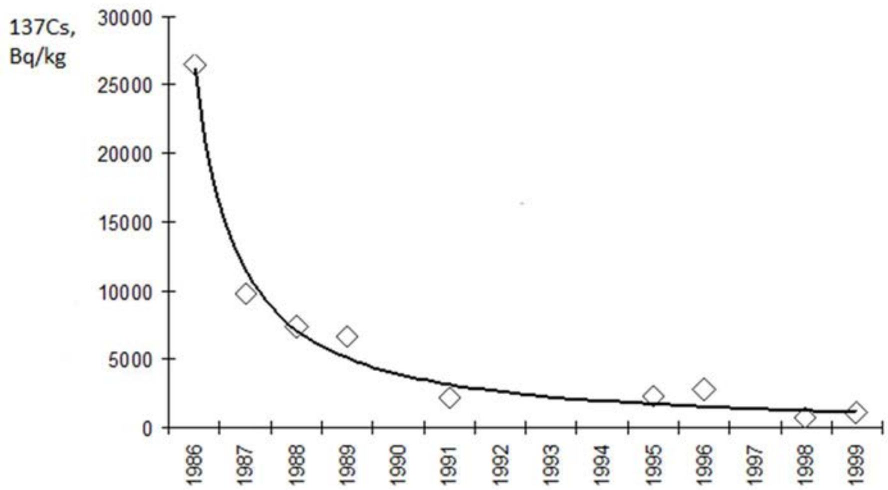


FIG. 31. Time dynamics of ^{137}*Cs content in soft tissues of Dreissena mollusks in the cooling pond in 1986 – 1999 (based on data of [55]).*

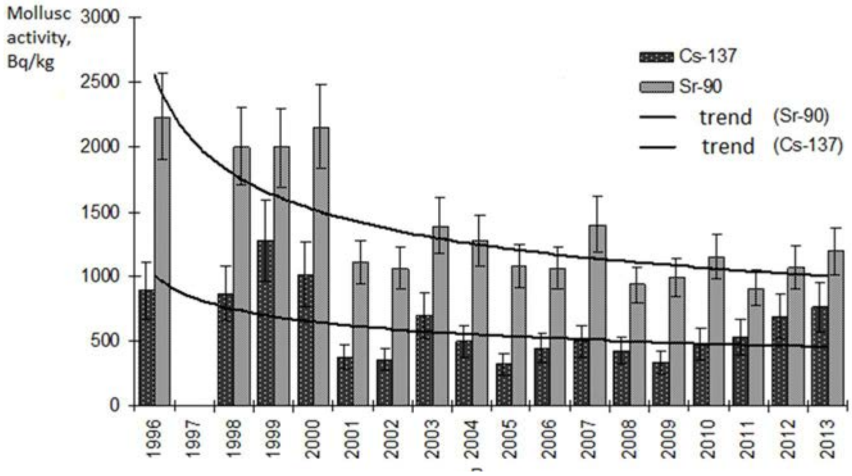


FIG. 32. Time dynamics of ^{137}Cs and ^{90}Sr content in Dreissena in the cooling pond in 1999 –2013 (based on data of [25]).

The observed dynamics of radionuclide activity in mollusks in the cooling pond can be explained by decrease of water activity, as well as by changes of thermal and hydrochemical regime of the cooling pond after shutdown of the last rector of ChNPP in 2000 [25].

3.6.3. Fish

During 1986–1987 the ^{137}Cs activity concentration in muscle of fish in the cooling pond reached 90 – 613 kBq/kg, which exceeded the pre-accident level by a factor of about ~ 10^4. During the 1987–1988 the radioactivity of fish has significantly decreased, reaching relatively stable levels in 1993–95 [58–62].

As an example of dynamics of ^{137}Cs activity in muscle of silver carp (*Hypophthalmichthys molitrix*) in 1987–1995 is shown in *FIG. 33*.

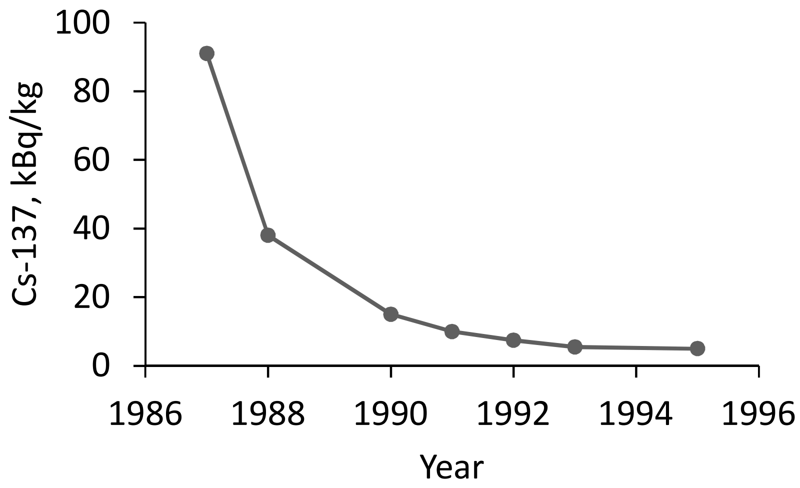


FIG. 33. Time dynamics of ^{137}Cs concentration in muscle of the silver carp (Hypophthalmichthys molitrix) in 1987–1995 (based on data [59]).

Studies of fish in the cooling pond carried out in 1997–2005 [54, 63] have shown that ^{90}Sr activity in fish ranged from 27 to 680 Bq/kg (on average 220 Bq/kg).

The ^{137}Cs in fish ranged from 930 to 10500 (average 3950) Bq/kg. The maximum ^{137}Cs activity concentration was observed in predatory fish species, where activity by a factor of about ~4 exceeded similar parameter for non-predatory fish. Thus, fish in the cooling pond demonstrated the effect of the trophic level of species on accumulation of ^{137}Cs.

Results of observations during 2006–2011 [64] show that mean radionuclide content in fish during the indicated period has not changed significantly. For most non-predatory fish species specific activity of ^{137}Cs did not exceed 2000 Bq/kg, however for some predatory species, such as perch (*Perca fluviatilis*), the ^{137}Cs activity has reached 9200 Bq/kg. The ^{90}Sr activity ranged from 86 to 245 Bq/kg.

Content of ^{90}Sr in the fish in the cooling pond in 2006 – 2011 almost always exceeded the Ukrainian permissible level in foodstuffs (35 Bq/kg) on average by a factor of 6 (maximum – by a factor of 20). The ^{137}Cs content in fish exceeded the permissible level (150 Bq/kg) on average by a factor of 26 (maximum – by a factor of 70).

3.6.4. Activity inventory in different components of aquatic biota

The IHB [25] has carried out estimation of radionuclide inventories in main biota-related components of the cooling pond in 2012–2013 (TABLE 16).

According to these estimates the main inventories of ^{90}Sr and ^{137}Cs are associated with the zoo-benthos and zoo-periphyton, as well as with the flaps of the dead *Dreissena* mollusks in bottom sediments. For ^{137}Cs important parts of inventory are also associated with the higher aquatic plants (13.4%) and fish (10.1%).

The total inventory of ^{137}Cs and ^{90}Sr in “biota-related” components in 2012–2013 was estimated 30–37 GBq and ~ 46 GBq respectively. Still the main radionuclide activity inventories in the cooling pond system are associated with bottom sediments (260±80 TBq of ^{137}Cs, and 55±11 TBq of ^{90}Sr, see Section 3.2.3) and water (~ 150 ±30 GBq of ^{137}Cs and similar inventory for ^{90}Sr, see Section 3.3) of the cooling pond.

TABLE 16. ESTIMATES OF RADIONUCLIDE INVENTORIES IN MAIN BIOTA-RELATED COMPONENTS OF THE COOLING POND IN 2012–2013 (*based on data [25]*)

Species (components)	^{90}Sr		^{137}Cs	
	GBq	%	GBq	%
Macrophytes:				
Emergent plants	0.62	NA	3.43	NA
Submerged plants	0.11	NA	0.87	NA
Filamentous algae	0.008	NA	0,21	NA
Sub-total	0.74	1.6	4.5	13.4
Phyto-perephyton	0.021	0.05	0.15	0.45
Phyto-plankton	0.011–0.025*	0,04	0.6–1.4*	2.95
Zoo-plankton	0.018–0.2*	0.24	0,22–2,42*	3.9
Zoo-benthos	14.9	32.5	9.8	29.2
Zoo-periphyton	3.25	7.1	2.35	7.0
Fishes	0.05–0.17	0.24	1.5–5.3	10.1
Shells of *Dreissena***	26.7	58.2	11.0	32.9
Total	45.6–46.0	100	30.2–36.9	100

Notes: *radionuclide inventories in phyto and zoo-plankton are calculated using transfer coefficients of the data base ERICA Assessment Tool 1.0 (Version November 2012);
**shells of dead mollusks which are present in the bottom sediments of the cooling pond

3.7. CONTAMINATION OF THE SURROUNDING TERRITORY

3.7.1. Surface contamination densities of the surrounding territory by radionuclides

Considering remedial options for the cooling pond, it is important to understand the overall radiological context of the surrounding territory.

The northern part of the pond which adjoins the industrial site of ChNPP is situated in a highly contaminated area with the average surface contamination densities of 5–10 MBq/m^2 with respect to ^{137}Cs and ^{90}Sr, and about 0.1–0.2 MBq/m^2 with respect to $^{239+240}Pu$ (FIG. 34). Here radioactive fallout was caused mainly by the so called “Northern” (or “Belorussian”) radioactive trace containing fuel hot particles.

The territory surrounding the southern part of the pond is characterized by much lower surface contamination levels (e.g. ^{137}Cs surface contamination density of 0.5–1 MBq/m^2). Here contamination was associated with the “Southern” trace of release associated with the condensation aerosol particles.

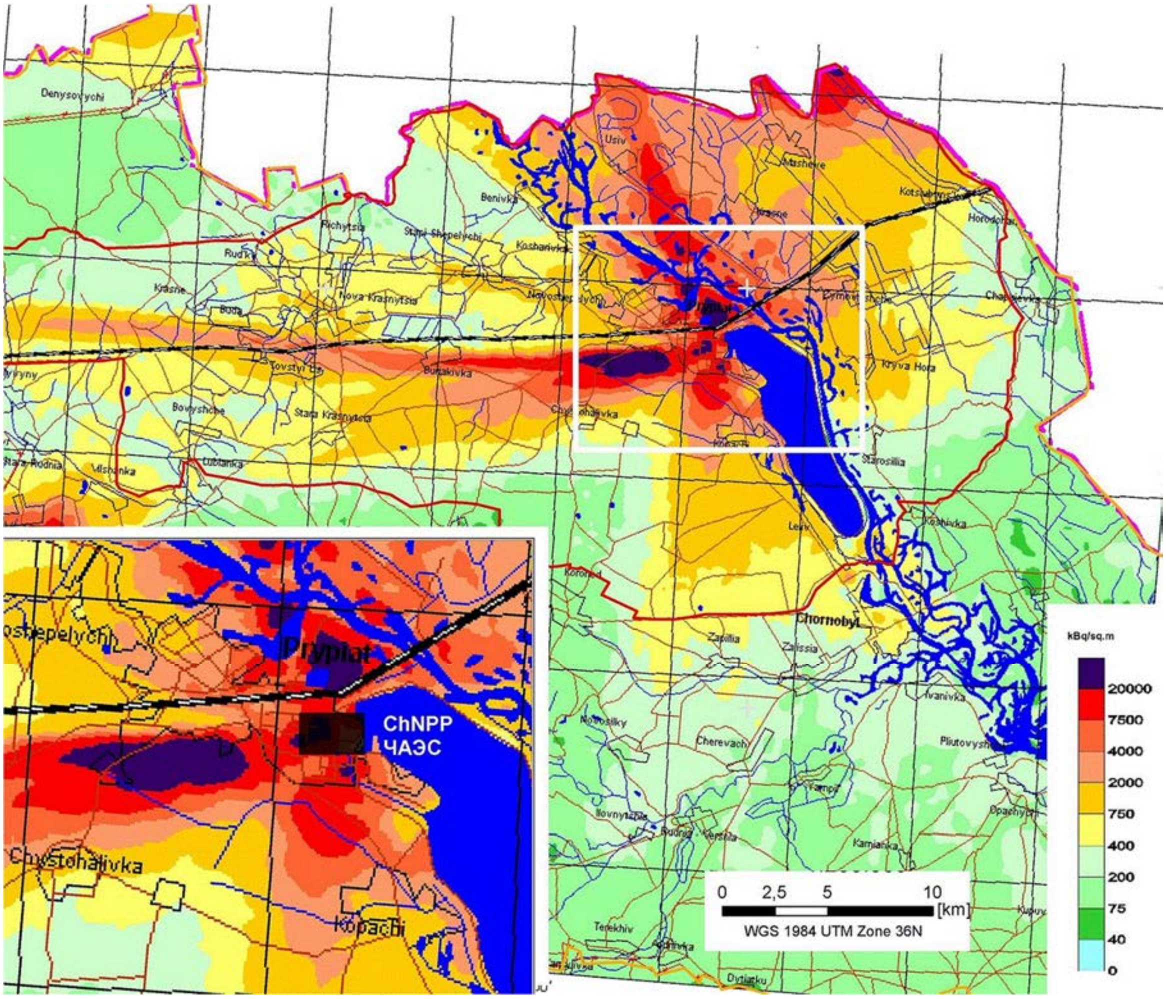


FIG. 34. Contamination of the territory of the 10 km zone of ChNPP by ^{137}Cs (for 1997) (based on data of the Ukrainian Institute of Agricultural radiology).

Radioactive contamination pattern of the bottom sediments of the cooling pond with the “hot spot” in the northern part of the pond correlates to some degree with the surface contamination patterns. However, it was likely influenced also by liquid releases from the industrial site of ChNPP (reflected in the “hot spot” in the mouth of the outflow channel) and secondary redistribution of silt material (containing hot particles) to the deeper pond areas (FIG. 16).

The contamination levels of bottom sediments of the pond on average are comparable to the levels of contamination of the surrounding territory. The mean surface contamination density of sediments with respect to ^{137}Cs in the shallow part of the pond (< 7.5 m) subject to drying in case of the cooling pond drawdown was estimated at 3 MBq/m^2, while the maximum “hot spots” in this zone reached 10 MBq/m^2 [5].

3.7.2. Radioactive waste localization and storage sites

Important aspect of the cooling pond remedial planning was that the cooling pond, as a large hydro-technical object, significantly influenced hydrogeological conditions on the whole ChNPP site. The Sarcophagus covering the damaged Unit 4 of ChNPP and a number of radioactive waste storage and disposal sites are situated in the immediate vicinity of the cooling pond.

Influenced by the cooling pond, groundwater levels at the Sarcophagus site during 1992–2012 ranged from ~109.5 to 111 m a.s.l. The lower marks of the floor of premises of the engine room and reactor compartment of the NPP constitute 108.8 m and 110 m a.s.l respectively, which is lower than mentioned above groundwater levels. This caused groundwater ingress to the power plant basement premises, with the estimated volume of 3500 m^3/year. The groundwater had to be pumped out, and (in view of high activity concentrations) had to be treated as liquid low level radioactive wastes by the NPP services [8].

Map showing the layout of radioactive waste storage and disposal sites in the 10 km zone of ChNPP is shown in FIG. 35. Two "legacy" Radioactive Waste Disposal Sites (RWDS) – "Podlesny" and "3rd Stage" shown on the map contain higher activity radioactive wastes from the decontamination activities at Sarcophagus site in 1986–88. Of specific concern were waste storage conditions in RWDS "3rd Stage" (with the estimated activity inventory of 7.5 10^{13} Bq in 2000) which represents below surface concrete vault, and is situated in the immediate vicinity of the cooling pond on an artificial "isle" formed by the pond and outflow channel. Survey of facility carried out in 1996 found out that the basement of facility was flooded by groundwater [65].

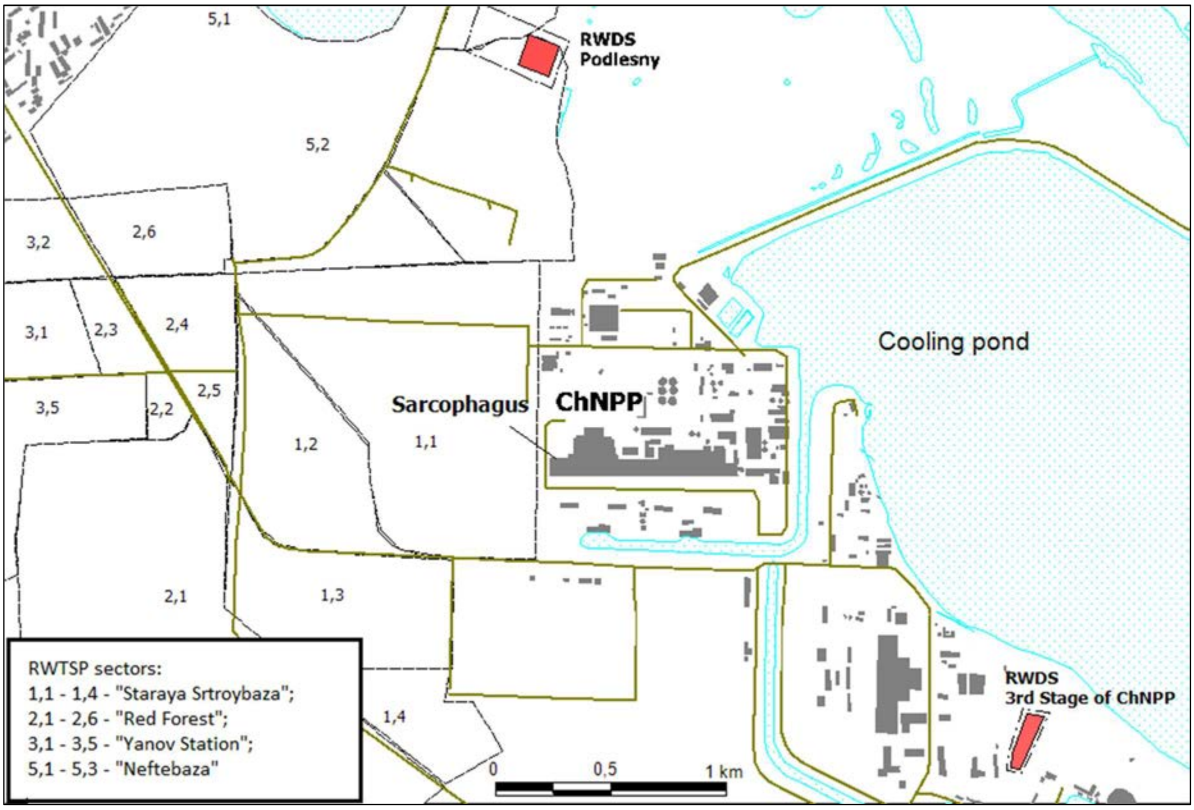


FIG. 1. Radioactive Waste Temporary Storage sites (RWTSP) and Radioactive Waste Disposal Sites (RWDS) situated in the vicinity of the cooling pond of ChNPP.

The so-called “Radioactive Waste Temporary Storage Sites” (RWTSP) represent trenches with wastes from clean-up activities carried out at ChNPP in 1987–88 (e.g. soil, vegetation, construction debris etc.). The total amount of these trenches (subdivided in “sectors”) (FIG. 35) is about 800. The amount of the low-level radioactive wastes stored in RWTSP was estimated at ~ 1.4 10^6 m^3 while the total stored activity was estimated at 3.5 10^{14} Bq [66].

Many of RWTSP sectors are situated in unfavorable hydrogeological conditions, and they have represented during the post-accident period sources of intensive radionuclide migration to groundwater.

Therefore previous remedial analyses of the cooling pond often stressed importance of coordinating the decommissioning strategy for the cooling pond with the management strategy for other radiation- hazardous facilities and objects, which are situated in the zone of influence of the pond [4, 5].

4. A PRIORI ASSESSMENT OF THE ENVIRONMENTAL IMPACTS OF THE WATER LEVEL DRAWDOWN THE COOLING POND

4.1. WATER LEVEL DRAWDOWN IN THE POND AS AN ULTIMATE DECOMMISSIONING OPTION

4.1.1. Water level drawdown in the pond as an ultimate decommissioning option

With closure of the ChNPP and shutting down of the reactors there is no need to maintain the cooling pond in its previous volume as a technological cooling water reservoir for the turbine condensers, heat-exchanging equipment in the generator hall of the NPP etc. [4].

Maintaining the water level in the pond is not a viable long-term option especially due to the related high operation and maintenance cost. The maintenance of the pond was associated with significant spending of about 600000 US $ per year, which included costs for electricity supply, staff wages, dam maintenance costs etc. (as in 2011 [8]). In addition, most of the equipment of the pumping station was by 2012 already at the end of its life cycle, and large investments were required to replace the terminated equipment.

Other negative aspects of maintaining the operational water level in the cooling pond (i.e. ~ 110.5–111.0 m a.s.l.) included [4, 7, 8]:

- risk of the cooling pond dam breach (see Section 4.1.3);
- continued radioactivity transport to Pripyat River due to seepage from the pond (see Section 3.5);
- negative influence of the pond on the hydrogeology conditions in surrounding areas – e.g. creation of the high groundwater levels at Sarcophagus site and adjacent radioactive waste storage and disposal sites (see Section 3.7.2).

Therefore, drawdown of water level in the pond (in a natural or controlled mode) has been considered as an ultimate option for the Chernobyl pond decommissioning in almost all previous pre-design research projects and feasibility studies [1, 2, 4–8].

The water level drawdown in the pond as a decommissioning option however is entailing new potential risks. The bottom sediments, which accumulated the main inventory of radioactivity within the cooling pond system (see Section 3.2), become the major media of concern [2, 4, 5].

Therefore, special attention in decommissioning and remedial designs for the cooling pond was focused on assessing risks posed by the contaminated bottom sediments, and on developing remedial designs to address this problem.

A more systematic overview of potential environmental impacts with the pond drawdown is given in the next paragraph.

4.1.2. Overview of potential environmental impacts with the pond drawdown

Resuspension and atmospheric transport of the highly contaminated bottom sediments on the dried-up parts of the pond bottom was usually considered as a major risk factor in the cited above previous decommissioning and remedial analyses of the cooling pond.

Similar accidental scenario has occurred in 1967 at Chelyabinsk-65 site in the Southern Ural region in USSR when strong winds have dispersed dried up radioactively contaminated bottom sediments of the Karachay Lake, which was used by Mayak Plant for discharging of liquid radioactive waste. This resulted in dispersion of some 2.2 10^{14} Bq (6000 Ci) of radioactive substances over the area of ~ 1800 km^2 [10].

Other identified potential impacts and risk factors of the water level drawdown in the cooling pond include [4–8]:

- Risk of fire of the dried-up vegetation growing on top of the highly contaminated bottom sediments and atmospheric dispersion of radioactivity;
- External irradiation of staff of the ChNPP from the exposed bottom sediments;
- Increased mobility of radionuclides from fuel particles in exposed bottom sediments due to changed bio-geochemical environment;
- Infiltration and groundwater transport of radioactivity from the exposed bottom sediments to Pripyat River;
- Massive dying out of biomass (fish, mollusks) in the pond leading to deterioration of ecological situation at the site (“catastrophic ecological consequences”).

These potential impacts and risk factors are analyzed in more detail in the subsequent sections of this chapter.

4.1.3. Risks associated with the cooling pond dam breach

As outlined in Section 2.1.3, the dam of the cooling pond historically had serious enough geotechnical stability problems related to soil suffosion in the dam segment in the vicinity of the pumping station, as well as due to Pripyat River bank erosion during the high flow events.

Analyses of potential radiological consequences of the breach of the dam of the cooling pond were carried out in [5]. The modeled accidental scenario assumed that a breach in the dam is formed, and dispersion of radioactively contaminated water and sediment occurs in downstream direction from the pond along the Pripyat River channel down to the Dnieper River system. It was assumed that the resulting overland flow of water is also remobilizing (washing-out) radionuclides from the adjacent contaminated floodplain soils of Pripyat River.

Simulation of propagation of overland flow from the pond was carried out using the 2D flow and transport model COASTOX, where the hydrodynamic module is based on the full Saint

Venant equation, while radionuclide transport module simulated concentration of radionuclides in water taking into account mixing of contaminated flux from the pond with water of Pripyat River, wash-out of radionuclides from floodplain soils, etc. The impact on the Dnieper River system was modeled using the 1-D model RIVTOX, which provides the cross-section averaged radionuclide concentration in river water and sediment.

Fishermen and other downstream populations using water from the Pripyat – Dnieper River system were considered as a critical group. The COASTOX and RIVTOX models are base modules of the European RODOS system for nuclear emergency management [67]. These models were configured and used previously to assess hydrologic transport of Chernobyl fallout radionuclides in the Pripyat – Dnieper River system [68].

The modeling has shown that water flow rate in the dam breach can reach up to 2200 m^3/s. However, the flooding of soils will be largely limited to Pripyat floodplain along the river channel in the vicinity of the pond. For the "worst case" scenario modeled (i.e. for the assumed width of the dam breach of 150 m), the predicted resulting ^{90}Sr concentration in Kiev Reservoir increased by 0.45 Bq/l, while in the other downstream reservoirs along the Dniper River it increased by 0.2–0.35 Bq/l (FIG. 36). The predicted ^{137}Cs concentrations in Dnieper were of an order of 0.01 Bq/l (or less). The estimated maximum individual doses to the critical group (fishermen at Kievskoe Reservoir) were estimated at 70 µSv/year [5].

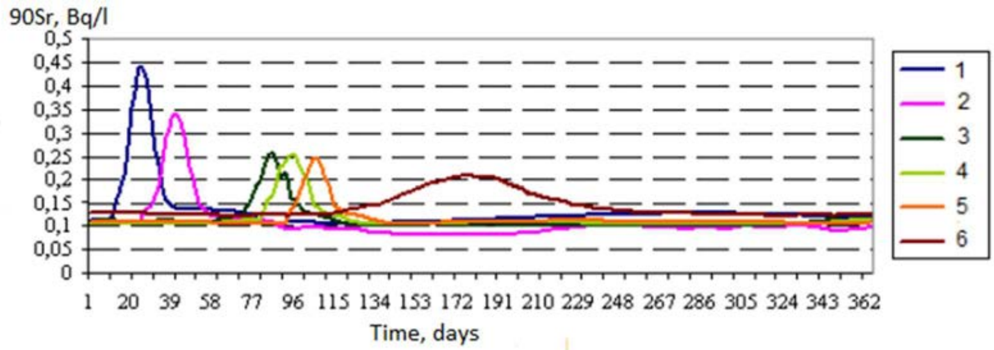


FIG. 36. Simulated ^{90}Sr activity concentrations in then reservoirs of the Dnieper River cascade following the breach of the dam of the cooling pond: 1-Kievskoe; 2-Kahovskoe; 3-Kremenchugskoe; 4-Dneprodzeginskoe; 5-Dnepropetrovskoe; 6-Kahovskoe (based on data [5]).

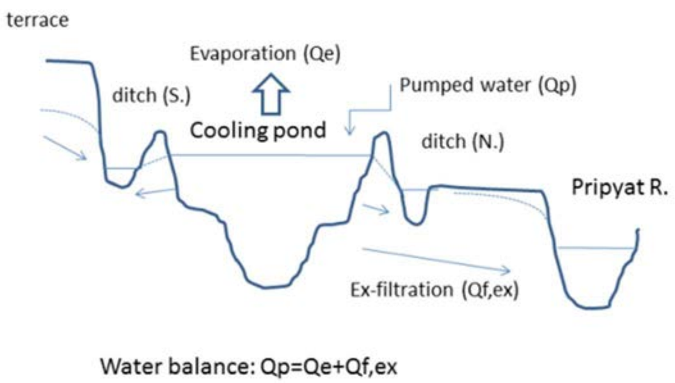
Thus, simulation has shown generally low radiological risk to the downstream populations caused by the possible failure of the dam of the cooling pond.

However, such accident would result also in physical risks caused by flooding of the surrounding areas. In addition, such accident will abruptly eliminate technological water supply to the NPP (without the replacement facility), leading to the risks of further accidental situations caused by termination of technological water supply. Negative public perception of such accident and related social impact were also expected [8].

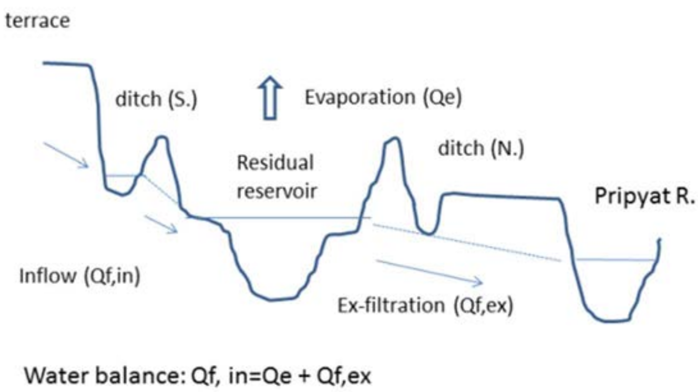
4.2. PREDICTION OF THE RATE OF THE WATER LEVEL DRAWDOWN IN THE POND AND OF THE END-STATE HYDROGEOLOGICAL CONDITIONS

In order to assess consequences of the water level drawdown in the pond, it is important to understand the time dynamics of this process, as well as the resulting configuration of the pond (or residual lakes) shoreline and exposed bottom sediment areas under different climatic conditions.

Under natural drainage conditions (assuming that pumping of water from the Pripyat River to replenish the pond is stopped) the decrease of water level in pond will be governed by seepage losses and evaporation losses from the pond (FIG. 37A). These water losses will evolve in time due to changing area of the pond (evaporation losses) and due to changing hydraulic boundary conditions (in case of seepage losses). The water level in the pond will proceed until new quasi-equilibrium state will be reached for the residual reservoir(s), where water inflows to the reservoir (inflowing groundwater, precipitation, surface run-off) are balanced by the outflows (groundwater ex-filtration, evaporation) (FIG. 37B).



(A). Initial condition of the pond (before drawdown)



(B). End state condition

FIG. 37. Scheme illustrating water level drawdown in the pond and related driving factors and water balances.

4.2.1. Modeling tool: Regional groundwater flow model of the Chernobyl exclusion zone

Modeling predictions of water level drawdown in the cooling pond were carried out using the regional groundwater flow model of the Chernobyl exclusion zone (ChEZ) developed in the Institute of Geological Sciences (IGS) [69].

This model was developed and continuously refined by the IGS since 1986, and was used for a number of projects, including optimization of the hydrogeological monitoring network in ChEZ, estimation of radionuclide transport to river network, safety assessment of radioactive waste repositories in ChEZ etc. [47, 70–72].

The model was developed using the finite-difference numerical code MODFLOW [45] using the Visual Modflow pre / post-processor software [73].

The filtration domain of the model covers the territory of about 30×30 km (FIG. 38). The boundaries of the filtration model are the Pripyat, Uzh, Sakhan and Ilya Rivers.

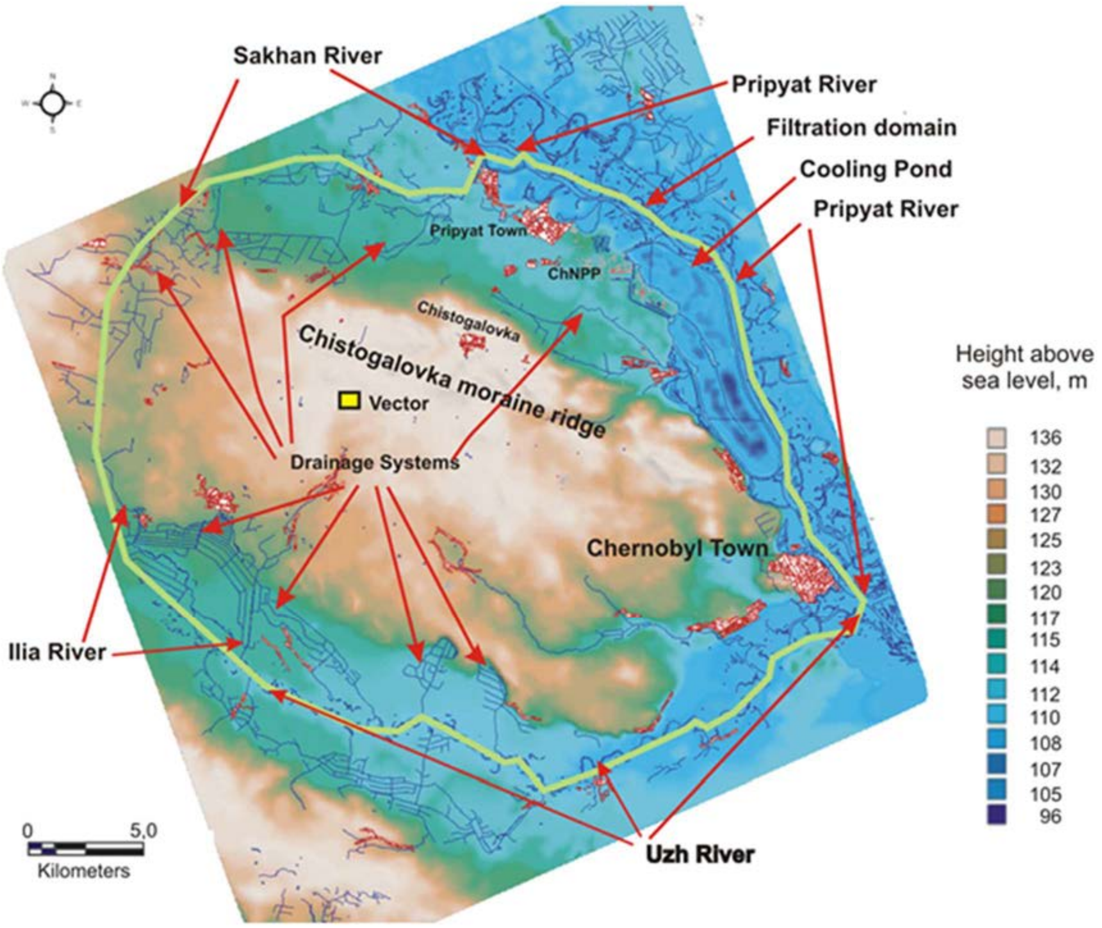


FIG. 38. Geographical area covered by the groundwater flow model of ChEZ and respective boundary conditions.

The computational grid of the regional model has a variable grid size along axes X and Y. Representation of the flow domain of the groundwater flow model of ChEZ on numerical grid is shown in FIG. 39. The size of numerical cells of the model varies from 20 m x 20 m to 500 m x 500 m.

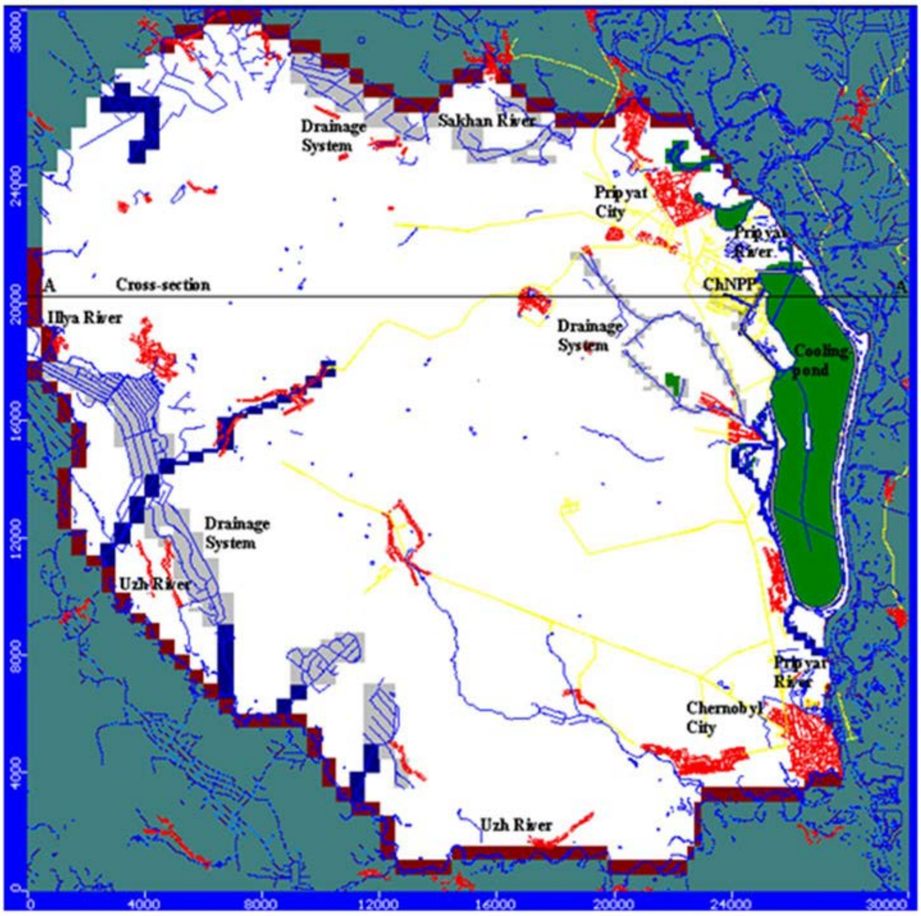


FIG. 39. Representation of the flow domain of the groundwater flow model of ChEZ on numerical grid.

The model encompasses two aquifers belonging to the "zone of active water exchange": the upper unconfined in Quaternary-Neogene deposits, and lower confined aquifer in Eocene deposits (FIG. 40). The unconfined aquifer is separated from the confined aquifer by a low permeability aquitard layer composed of clays and marls of Kiev suite of Palaeogene (see section 2.2.2 for more detail on site hydrogeology).

The overall model calibration was carried out using data of observations of water levels in monitoring wells located in ChEZ. The fitted parameters were hydraulic conductivity of aquifers and atmospheric precipitation infiltration recharge rate values.

Data of the experiment on controlled drawdown of the water level in the cooling pond (for estimation of seepage losses) carried out in in July–August 2001 (see Section 2.1.4) were used to calibrate model for specific values of hydraulic conductivity of the geological deposits of the dam and floodplain soils in the vicinity of the cooling pond [74].

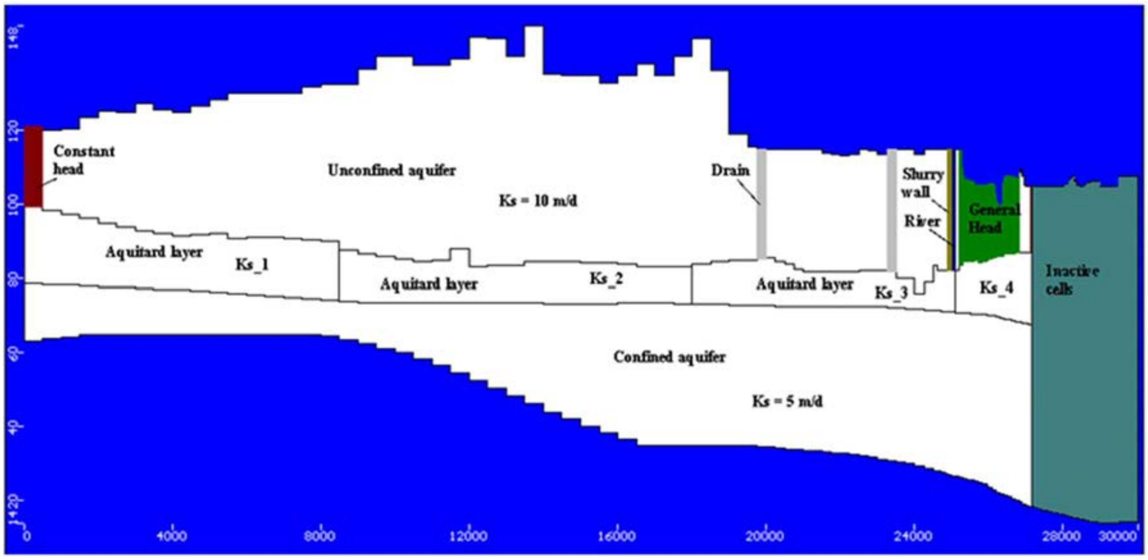


FIG. 40. Vertical cross-section of the flow domain of the model along the line A-A (the line of section is shown in FIG. 39).

Results of model calibration are summarized in TABLE 17. Good agreement between modeling and experimental data was reached for the discharge rate of the drainage ditches of the pond. The model however provided by ~20% smaller total seepage losses from the pond compared to the experimental data. This can be due to the fact, that experimental data likely included concentrated leakages through suffusion channels in the dam segment close to the pumping station (see section 2.1.3). The resulting fitted hydraulic conductivity (K_f) values are: K_f=10 m/day for the unconfined aquifer in Quaternary deposits, and K_f=5 m/day for the confined aquifer in Eocene deposits. These values are in reasonable agreement with the results of hydraulic tests, being closer to the higher end estimates of hydraulic conductivity from the field tracer tests (see section 3.4.1.1).

TABLE 17. COMPARISON OF SEEPAGE LOSSES BASED ON OF THE EXPERIMENTAL DATA AND GROUNDWATER FLOW MODEL CALIBRATION (*based on data [74]*)

Data source	Drainage ditches, m^3/day	Total seepage losses, m^3/day
Experiment	176000	290000
Modelling	179000	232000

Detailed description of the regional groundwater flow model of ChEZ can be found in [72].
In cooling pond decommissioning and remedial analyses, the described above regional groundwater flow model was used for a number of modeling tasks: to evaluate time dynamics of water level drawdown in the pond (section 4.2.3); to predicting the end-state hydrogeological conditions (section 4.2.4); and to estimate influence of water level drawdown in the pond on hydrogeological conditions at other adjacent hazardous sites (section 4.6.2).

4.2.2. Methodology for modeling the water level drawdown in the pond

Water level drawdown in the cooling pond was expected to proceed through two stages [74]:

1. Decrease of the water level in pond from initial value (110.5–111.0 m) to about 106.0 m. At this stage the integrity of the water surface in the whole reservoir shall be preserved. When water level in the pond will drop below ~ 107.0 m, the drainage ditches will dry up, and the subsurface seepage path from the pond to Pripyat River will increase significantly.

2. Decrease of water level in separate residual water reservoirs within the area of the pond from 106 m to ~ 104.5±1 m. The water levels in separate reservoirs will differ depending upon balances of inflow and outflow groundwater fluxes, evaporation, precipitation etc. (see FIG. 37)

In conditions of maintaining of the operational level in the pond, seepage losses significantly dominated evaporation losses (see section 2.1.4). Therefore, at early stages of the cooling pond drawdown dynamics of process are determined first of all by the magnitude of seepage losses and their changes over time. The seepage losses decline in time due to the combined effect of two factors: (a) lowering water in the pond (and related decrease in hydraulic head difference between the pond and Pripyat River), and (b) retreat of the pond shoreline and respective increase in the length of the flow path from the pond to Pripyat River.

Bugai and Skalskyy [74] have modeled the time dynamics of water level drawdown in the pond using the following ordinary differential equation, describing water balance in the pond.

Water losses from the pond can be calculated as:

$$dV = -Q(h,t)\,dt,$$

where dV is change in the volume of water in the pond (m^3); $Q(h,t)$ are water losses from the pond, (m^3/day); dt is time interval (days).

Water losses from the pond can be further detailed as

$$Q(h,t) = Q_f\,dt + Q_e\,dt - V_p\,dt,$$

where Q_f are seepage losses (m^3/day); Q_e are evaporation losses (m^3/day); and V_p are precipitations (m^3/day).

Substituting the expression

$$dV = S(h)\,dh,$$

where $S(h)$ is the water surface area of the pond (m^2), and dh is lowering of the water level (m) during the time interval dt, we arrive to the following ordinary differential equation describing time dynamics of the water level in the pond

$$S(h)\,dh = -Q(h)\,dt,$$
$$\frac{dh}{dt} = -\frac{Q(h)}{S(h)},$$

The above equation needs to be complemented by the initial condition

$$h|_{t=0} = H_o,$$

where H_o is the initial water level in the pond at time t=0.

The described above non-linear differential equation can be solved numerically (e.g. using the Runge-Kutta methods with linearization, or using the "predictor-corrector" scheme) to calculate water level in the pond $h(t)$ as a function of time.

Thus, to predict the rate of water level draw-down in the pond functions $Q(h)$ (water losses from the pond) and $S(h)$ (area of the pond), which are dependent of water level in the pond need to be known.

Area of the water surface in the pond as a function of the water level in the pond can be determined by the means of the Digital Elevation Model (DEM) of the pond bottom (see section 2.1.5.1, FIG. 7).

In order to estimate $Q(h)$, the seepage losses from the pond were estimated for different values of the water level in pond (h) using the described above (Section 4.2.1) regional groundwater flow model of the Chernobyl zone.

Once water level as a function of time is determined, the position of shoreline and the surface area of the pond as a function of time can be established.

4.2.3. Predicted water drawdown rates in the pond for different climatic scenarios

Water level drawdown rate in the cooling pond was modeled for the two climatic scenarios ("normal" and "dry "scenario") which differed by evaporation rates and hydrogeological boundary conditions (TABLE 18) [74].

"Normal" scenario corresponds to the average multi-annual meteorological and hydrological conditions of the Chernobyl exclusion zone (see section 2.2.1).

"Dry" scenario corresponds to extreme conditions: minimal amount of precipitation, maximum open water evaporation, minimal infiltration recharge rate values, minimal water levels in the river network. This scenario should be considered as an "enveloping" scenario.

TABLE 18. METEOROLOGICAL AND HYDROLOGICAL PARAMETERS FOR "NORMAL" AND "DRY" MODELING SCENARIOS FOR THE COOLING POND

Parameter	"Normal" scenario	"Dry" scenario
Evaporation from the water surface (taking into account precipitation), mm/year	200	700
Infiltration recharge to groundwater at floodplain of the Pripyat River, mm/year	200	0
Water level in Pripyat River, m a.s.l.	103.2	102

Seepage losses from the pond as a function of the water level in the pond estimated using the regional groundwater flow model of Chernobyl zone are shown in FIG. 41. When water level in the pond decreases by ~ 3 meters (from 111 to 108 m a.s.l.), the seepage losses are predicted to decrease by a factor of about ~5. Once water level drops below ~ 106 m a.s.l. the cooling pond splits into several isolated water reservoirs. At this water elevation seepage losses from the pond are comparable to evaporation losses, and further rate of water level decline will be determined to large degree by the meteorological conditions.

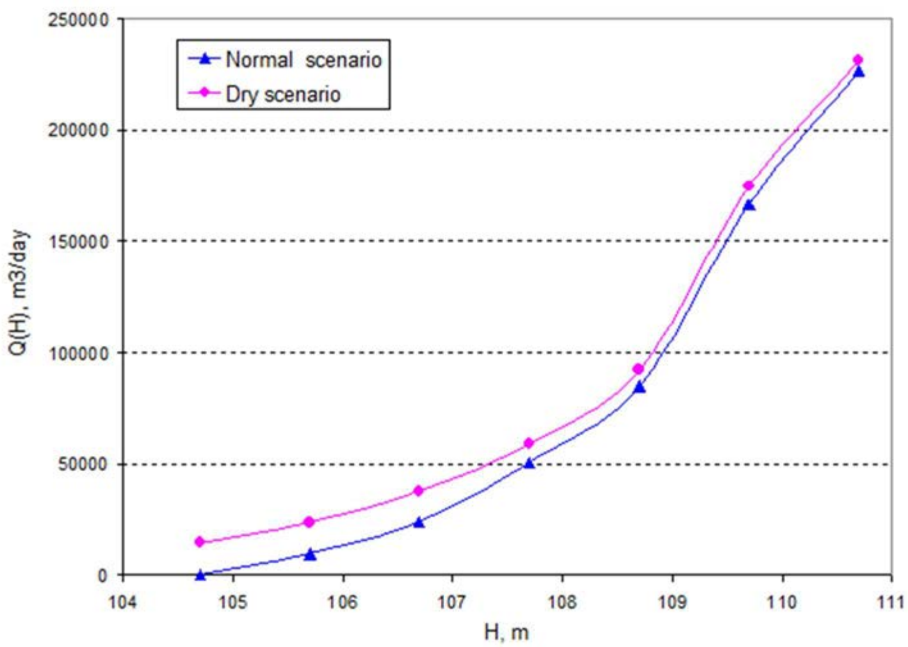


FIG. 41. Estimated seepage losses from them pond as a function of the water level in reservoir (based on data [74]).

Calculated graphs of water level decline in the pond as function of time in conditions of natural drainage are shown in FIG. 42. The expected time of water level decline in the pond to 105 m a.s.l. ranges for the modelled scenarios from 3 to 6 years.

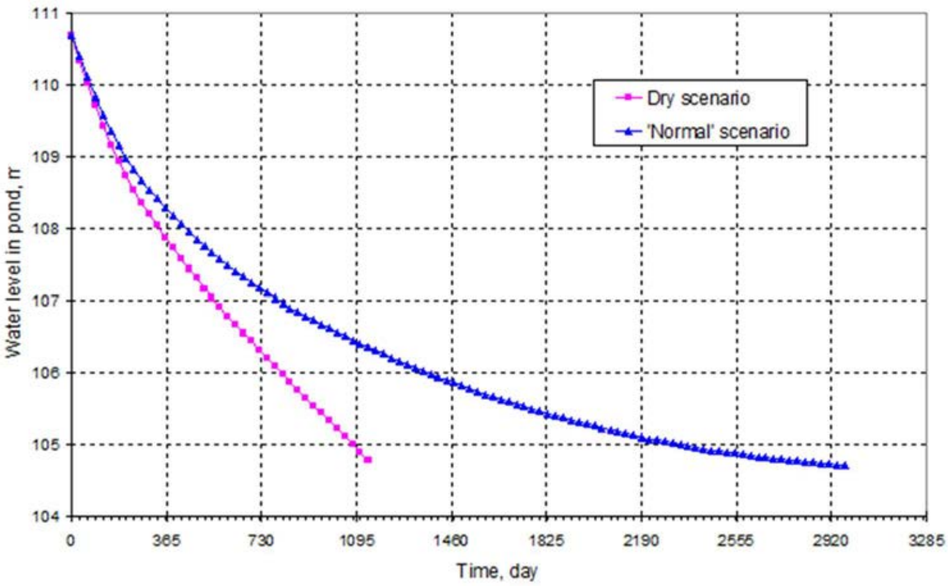


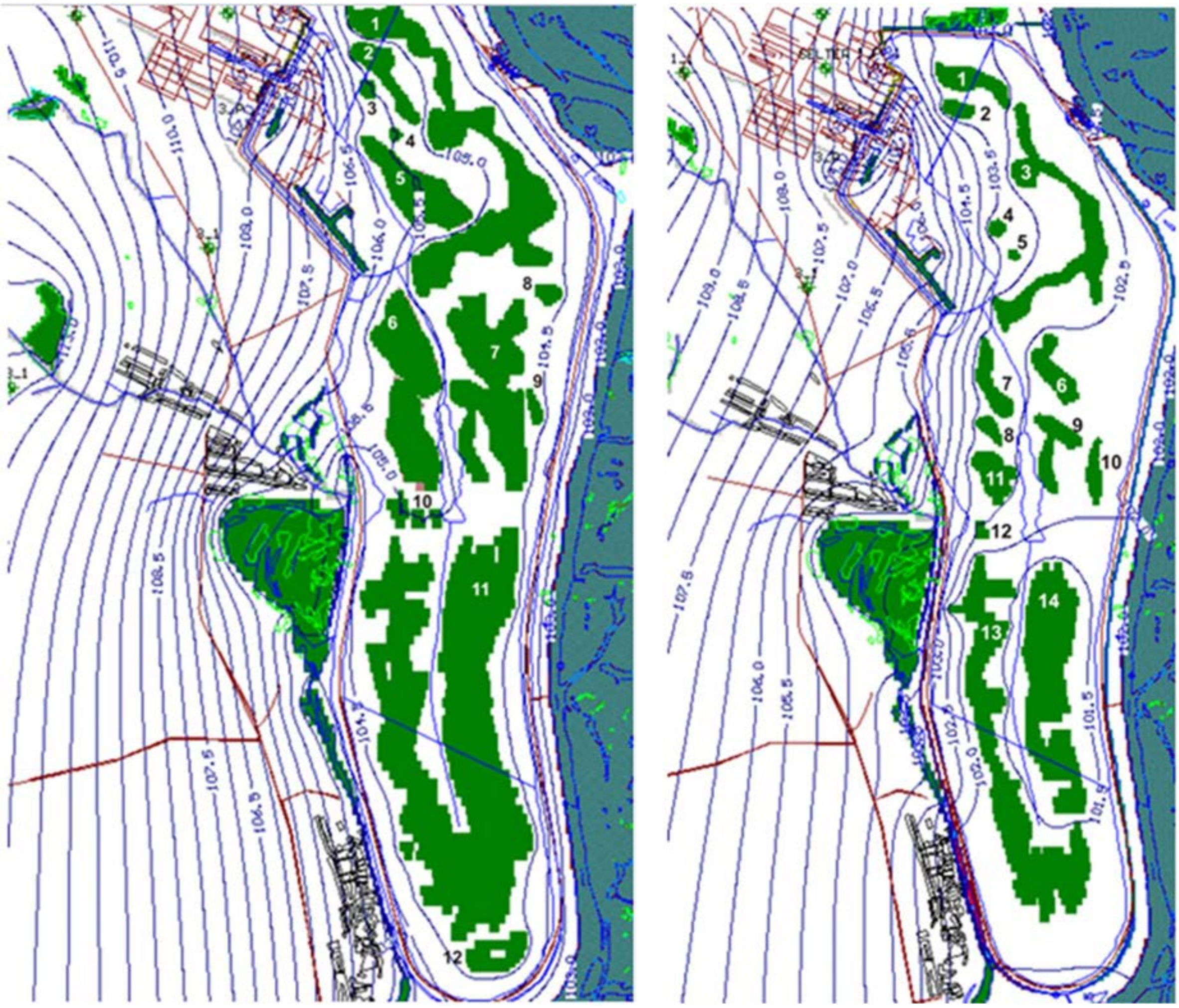
FIG. 42. Predicted dynamics of the water level drawdown in the cooling pond for different climatic conditions (based on data [74]).

4.2.4. End-state hydrogeological conditions for different scenarios

The water levels in the residual lakes in the bottom area of the pond, and related configuration of the shoreline were determined using the groundwater flow model described in section 4.2.1. Water levels were fitted using a "trial and error approach" in order to satisfy the water balance criteria for the residual lakes (i.e. that the equilibrium is reached between the groundwater inflow to lakes and groundwater outflow and evaporation rates; FIG. 37B).

This was done for the two meteorological scenarios assuming "normal" and "dry" conditions (see TABLE 18).

Modeling results are ae shown in FIG. 43 A and B. It can be seen that the predicted water levels and configuration of shorelines of residual lakes differ significantly depending on the assumed meteorological scenario.



(A) “Normal” climatic scenario (B) “Dry” climatic scenario

FIG. 43. Modeling prediction of the end-state (equilibrium) water levels in the residual lakes within the area of the cooling pond (based on data [41]).

For the “normal” scenario water levels in residual lakes vary from 105.5 m a.s.l. in northwest part of the pond bottom to 104.7 m in the southern part of the former pond. The area of the exposed bottom sediments is ~ 14.4 km^2 (FIG. 43A).

For the “dry” scenario water levels in residual lakes vary from 103.3 m a.s.l. in northwest part of the pond to 101.2 m in the southern part of the pond. The area of the exposed bottom sediments is ~ 18.6 km^2 (FIG. 43B).

Groundwater modeling results for “normal” and “dry” climatic conditions can be integrated to produce expected distribution of different landscape areas (dry, permanently flooded by water, and “transient” wetland areas) in the cooling pond following its drainage (FIG. 44).

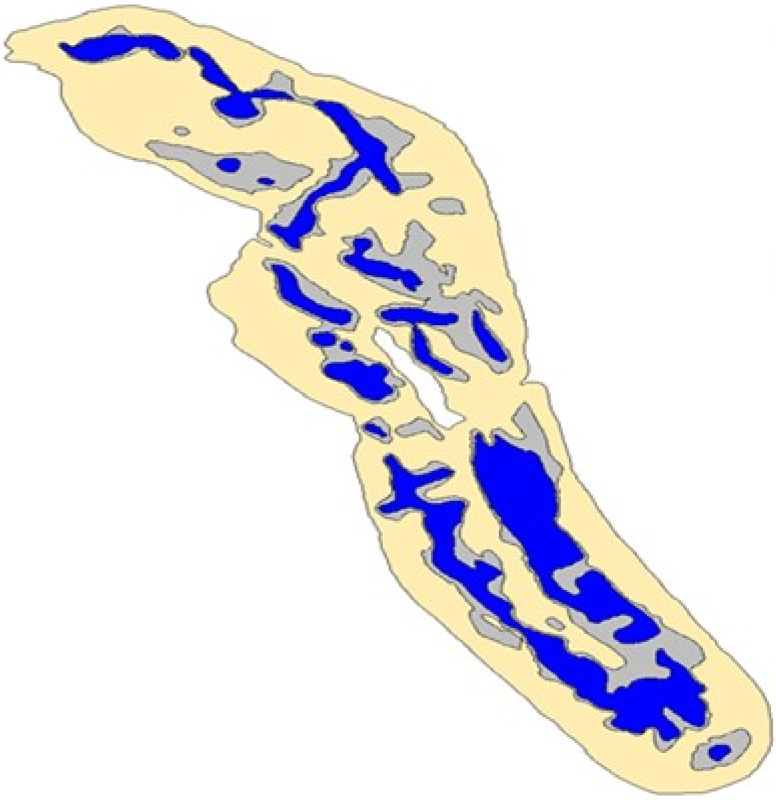


FIG. 44. Predicted bottom topography areas within the cooling pond following drainage: completely dried (yellow); completely covered by water (blue); and intermediate area (grey) to be considered as wetlands in wet seasons and to be exposed to the air during drought seasons (based on data [6]).

4.3. ANALYSIS OF RISKS OF THE ATMOSPHERIC TRANSPORT OF RADIOACTIVITY

4.3.1. Atmospheric resuspension of the dried up bottom sediments

Systematic and comprehensive, modeling analyses of wind transport of the dried-up exposed bottom sediments of the cooling pond were carried out in 2001–2003 [5, 14, 37].

These studies were further précised in the course of the feasibility study for the decommissioning of the cooling pond [8, 75].

4.3.1.1. Experimental studies of atmospheric resuspension of bottom sediments from the dried up water bodies in the 30 km zone

The described above modeling studies were complemented by experimental programme aimed at estimating parameters governing secondary transport of radioactive aerosols from the dried up bottom sediments in real-world conditions of the Chernobyl Exclusion zone [37].

Experimental studies on resuspension of dried up bottom sediments were carried out in 2001 at the field site at the left bank of the Pripyat River situated at 1–2 km northeast from the ChNPP at the drained dried up former wetland area. The bottom sediments in the wetland were similar to those encountered at the shallow depths in the cooling pond. Experimental studies included measuring radionuclide activity concentrations in the air and disperse composition of aerosols in the air (using impactor air samplers), as well as measuring the radioactive aerosol deposition rates on horizontal tablets. The list of analyzed radionuclides included ^{137}Cs, ^{90}Sr and $^{239+240}$Pu.

It was established that [37]:

- Resuspension coefficients for all radionuclides were practically the same and constituted about 5×10^{-10} m^{-1};
- The average rates of dry deposition of radioactive aerosols were similar for all radionuclides with values of an order of 2 cm s^{-1};
- The activity median aerodynamic diameter (AMAD) for all radionuclides was about 15 µm (TABLE 19).

The same (or very close) values of resuspension coefficients, deposition rates, and size composition of aerosols for different radionuclides indicated that all these radionuclides were likely present in the same chemical and physical form, that is in the form fuel hot particles [37]:

This conclusion from radioactive aerosol resuspension studies for bottom sediments conforms to the findings of radionuclide speciation in the bottom sediments of the cooling pond (see section 3.2.4), which have established that ^{90}Sr and transuranium isotopes in the bottom sediments of the cooling pond were mainly associated with fuel hot particles.

The derived parameters were applied for assessing potential atmospheric impact from the dried up bottom sediments of the cooling pond.

TABLE 19. DISTRIBUTION OF RADIOACTIVITY IN ACCORDANCE WITH AERODYNAMIC DIAMETER VALUES FOR THE DRIED UP BOTTOM SEDIMENTS (AVERAGE VALUES) (*based on data [37]*)

Activity median aerodynamic diameter (AMAD), µm	Fraction of aerosol in radioactive contamination
<0.9	0.017
0.9–2.4	0.012
2.4–6.8	0.099
6.8–15	0.175
15–32	0.460
>32	0.237

4.3.1.2. Scenarios of atmospheric transport of dried up bottom sediments from the cooling pond

Modeling of atmospheric transport of radioactivity from the cooling pond was carried out for two scenarios described below [37].

Scenario 1: Atmospheric transports during a year for the “normal” averaged multiannual meteorological conditions. The resuspension coefficient of 5×10^{-10} m^{-1} was used (see previous paragraph).

Scenario 2: Dust storm during summer period of 3 days duration with wind speed of 15 m/s. The D category of atmospheric stability was assumed. This scenario used a conservative value of the resuspension coefficient of 1×10^{-7} m^{-1}.

The assumed parameters for the dust storm were based on meteorological data records for the Chernobyl Exclusion Zone [76]. The probability of such scenario is approximately 0.01 y^{-1} [75].

Maximum extent of dried up bottom sediments of the cooling pond of ≈18 km^2 was assumed in atmospheric transport calculations (see section 4.2.4).

The drained cooling bond bottom was considered as the flat area with the heterogeneous distribution contamination based on bottom sediments mapping studies (see section 3.2.3).

Calculations endpoints included:

- additional terrestrial contamination by ^{137}Cs, ^{90}Sr, ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Am, and

- doses to reference persons caused by inhalation of the radioactive aerosols resuspended from the drained parts of the cooling pond.

Calculations were carried out for the adult reference person (e.g. staff member) situated at the territory of the ChNPP industrial site and in the Chernobyl city.

4.3.1.3. Modeling methodology for atmospheric dispersion of radioactivity

Atmospheric transport of aerosols was modeled using the standard Gaussian dispersion model [77, 78].

For the calculation purpose, the drained cooling pond bottom was sub-divided into the quasi-homogeneous (in terms of the contamination density of the sediment top layer) elementary areas with the size of 25 m x 25 m (point sources). Concentrations of radionuclides in the air was calculated by means of integration over all drained area (i.e. superposition of large set of point sources), and by of integration over size composition of aerosols.

The drained and adjacent surfaces were assigned the parameter of roughness of 10 cm.

The effective intensity of the point source-term (i.e. 25 m x 25 m plot) was calculated using the following expression;

$$q = K_a \text{ x } A_o \text{ x } S \text{ x } U,$$

Where A_o is the average surface contamination density of the upper layer (0–1 cm) of the bottom sediments (kBq/m^2), U is wind velocity (m/s), S is area of source (m^2), and K_a is resuspension coefficient (m^{-1}).

4.3.1.4. Dosimetry model

Calculations of the doses caused by the inhalation intake of ^{137}Cs, ^{90}Sr, ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Am were carried out using the dose model of the human respiratory tract presented in the ICRP Publication No. 66 [79]. The assumed referent inhalation volume for an adult was 2.25m^3/year. The considered radionuclides do not reach the equilibrium state in the organism during the modeled short periods of their intake, and for this reason the 50 year effective equivalent dose (50yr EED) was calculated. (This last approach complies with the recommendations of the Ukrainian regulatory document NRBU-97 [80]). For each radionuclide redistribution processes in human body was described using the bio-kinetic models presented in the ICRP Publication No. 30 [81].

4.3.1.5. Results of atmospheric transport calculations

Results of atmospheric transport calculations for Scenario 1 (“normal” wind conditions) and Scenario 2 (dust storm) are summarized in TABLE 20 (secondary contamination of land by atmospheric deposition) and in TABLE 21 (resulting inhalation doses to reference persons). To estimate of additional contamination in Chernobyl Town average value was calculated for 5 points evenly covering the city territory; for the territory of Industrial site of ChNPP, the average value for 6 points situated at 25 m to 200 m distance from the cooling pond was used.

Example graphs showing additional contamination of land by ^{137}Cs due to atmospheric transport of contaminated bottom sediments from the drained areas of the pond for different scenarios are shown in FIG. 45 to FIG. 47. Contamination patterns of land by other radionuclides generally mostly correlate with ^{137}Cs.

It can be seen that additional secondary contamination of land due to wind transport of radionuclides from the dried up bottom sediments will be very low compared to the existing contamination of the territory which have formed in 1986.

Additional contamination of land by ^{137}Cs at ChNPP site for the “normal” scenario is estimated at 6.4 Bq/m^2, while existing contamination levels of the territory adjacent to the cooling pond by ^{137}Cs are of an order of ~100 kBq/m^2 to~ 1 MBq/m^2 (see section 3.7.1).

TABLE 20. ESTIMATED LEVELS OF SECONDARY CONTAMINATION OF THE LAND DUE TO DEPOSITION OF RADIOACTIVE AEROSOLS CARRIED OUT BY WIND FROM THE COOLING POND BOTTOM (*based on data* [75])

Radionuclide	ChNPP		Chernobyl Town	
	"Normal" scenario	Dust storm	"Normal" scenario	Dust storm
^{137}Cs, Bq/m^2	6.4	37	0.08	5
^{90}Sr, Bq/m^2	1.5	7.4	0.02	1
$^{238,239,240}Pu$, Bq/m^2	0.07	0.33	9 10^{-4}	0.05
^{241}Am, Bq/m^2	0.08	0.4	0.001	0.06

TABLE 21. THE ESTIMATED INHALATION 50YR EED FOR STAFF DUE TO ATMOSPHERIC TRANSPORT OF RADIOACTIVE AEROSOLS CARRIED OUT BY WIND FROM THE COOLING POND BOTTOM, µSV (*based on data* [75])

Scenario	Location	
	ChNPP	Chernobyl Town
"Normal" scenario	0.52	0.009
Dust storm	3.0	0.34

Contamination levels due to dust storm can be order of magnitude higher compared to "normal" conditions, but still dust storm can potentially contribute only 0.02% y^{-1} or less to the existing contamination levels of the surrounding territory [75].

The estimated inhalation 50yr EED for staff due to atmospheric transport of radioactive aerosols carried out by wind from the cooling pond bottom for all scenarios was in the range of micro-Sievert, which is the safe dose range.

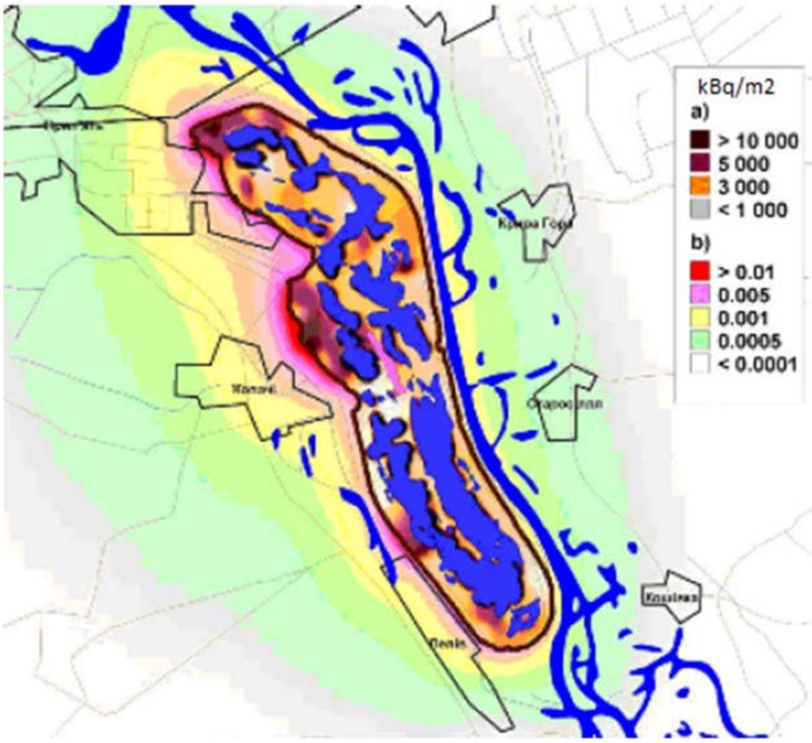


FIG. 45. Additional contamination of land by ^{137}Cs due to atmospheric transport of contaminated bottom sediments from the drained areas of the pond for "normal" scenario: a) surface contamination density of the drained area of the pond; b) surface contamination density of the surrounding territory (based on data [75]).

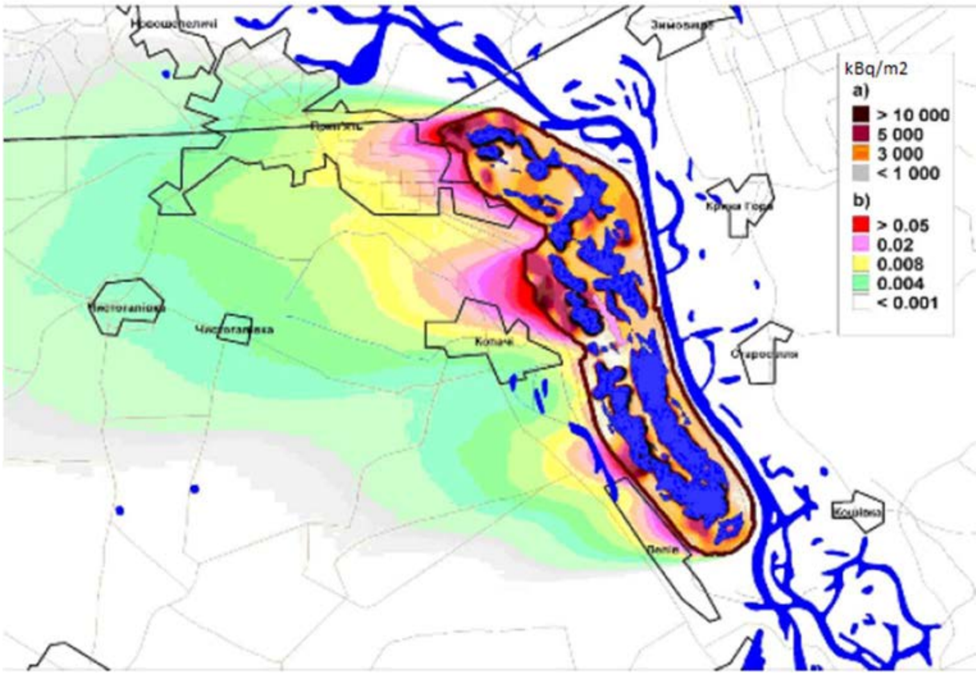


FIG. 46. Additional contamination of land by ^{137}Cs due to atmospheric transport of contaminated bottom sediments from the drained areas of the pond for "dust storm" scenario, for wind direction towards ChNPP: a) surface contamination density of the drained area of the pond; b) surface contamination density of the surrounding territory (based on data [75]).

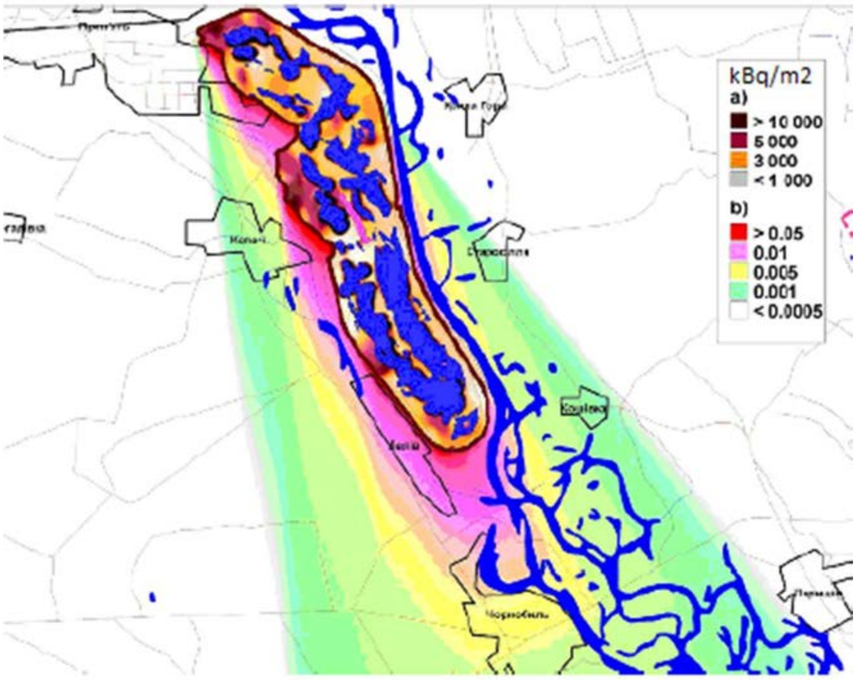


FIG. 47. Additional contamination of land by ^{137}Cs due to atmospheric transport of contaminated bottom sediments from the drained areas of the pond for "dust storm" scenario, for wind direction towards Chernobyl Town: a) surface contamination density of the drained area of the pond; b) surface contamination density of the surrounding territory (based on data [75]).

4.3.2. Fire of the dry contaminated vegetation growing on the drained pond bottom

4.3.2.1. Scenario of fire of the dry vegetation growing on the drained pond bottom

One of potentially hazardous scenarios of atmospheric transport of radioactivity is fire of dry vegetation growing on top of the contaminated sediments in the cooling pond during the dry period of the year [37, 75].

The modelled scenario assumed a fire of the contaminated vegetation growing on the dried-up bottom sediments, and the wind transport of radioactive products of biomass burning (ashes, residual not fully burnt biomass fragments). The wind speed of 1 m/s in direction of ChNPP or Chernobyl Town, and the D category of atmospheric stability were assumed. The assumed duration of the event was 5 days.

4.3.2.2. Modeling methodology and parameters

Similarly to scenario of the wind transport of the dried-up bottom sediments, the Gaussian model was used for modeling atmospheric transport of radioactivity due to dry vegetation fire on the drained pond bottom, and maximum area of dried up bottom sediments of the cooling pond of ≈ 18 km^2 was assumed in atmospheric transport calculations (see section 4.2.4).

Based on reference data of [82], the vegetation biomass production rate at the drained cooling pond bottom area was assumed to equal 0.2 kg/m^2 for the constantly dry areas, and 2 kg/m^2 for the seasonal wetland areas of the pond bottom (see section 4.2.4).

Radionuclide-specific parameters for the dry vegetation fire scenario are listed in TABLE 22.

It was assumed that the fraction of biomass activity which is remobilized by fire to atmosphere is 1%. This last value and AMAD data for radioactive aerosols (TABLE 22) are based on experimental data for grassland fires in the Chernobyl zone [83]. The radionuclide transfer coefficients to the vegetation are based on [46].

TABLE 22. RADIONUCLIDE-SPECIFIC PARAMETERS FOR THE DRY VEGETATION FIRE SCENARIO ON THE DRAINED BOTTOM OF THE COOLING POND

Radionuclide	AMAD, µm	Transfer coefficient to vegetation, (Bq/kg)/(Bq/kg)
^{137}Cs	12	5.0
^{90}Sr	23	7.3
Pu isotopes	10	3.9×10^{-3}
^{241}Am	10	4.8×10^{-2}

4.3.2.3. Results of atmospheric transport calculations

Results for atmospheric transport calculations are summarized in TABLE 23. Example graph showing additional contamination of land by ^{137}Cs due to atmospheric transport of radioactivity in case of grassland fire at the drained areas of the pond is shown in FIG. 48.

In case of dry grassland fire on the drained pond bottom estimated secondary contamination of the territory adjacent to ChNPP by ^{137}Cs and ^{90}Sr due to deposition of radioactive aerosols (see TABLE 23) is higher compared to other considered scenarios of atmospheric transport of radioactivity (TABLE 22), however even in this case, it still by a factor of 1500–3000 lower compared to minimum existing levels of contamination of the territory adjacent to the pond.

Resulting inhalation doses to staff are also with the negligible (µSv) range (see TABLE 23).

TABLE 23. ESTIMATED SECONDARY CONTAMINATION OF THE LAND DUE TO DEPOSITION OF RADIOACTIVE AEROSOLS AND INHALATION DOSES TO STAFF FROM VEGETATION FIRE AT THE COOLING POND BOTTOM (*based on data* [75])

Location	ChNPP	Chernobyl Town
Secondary contamination of land	NA	NA
^{137}Cs, Bq/m^2	58	12
^{90}Sr, Bq/m^2	55	8.5
$^{238,239,240}Pu$, Bq/m^2	4.5×10^{-4}	7.8×10^{-5}
^{241}Am, Bq/m^2	7.5×10^{-3}	1.2×10^{-3}
Inhalation 50yr EED for staff, μSv/year	1.9	0.3

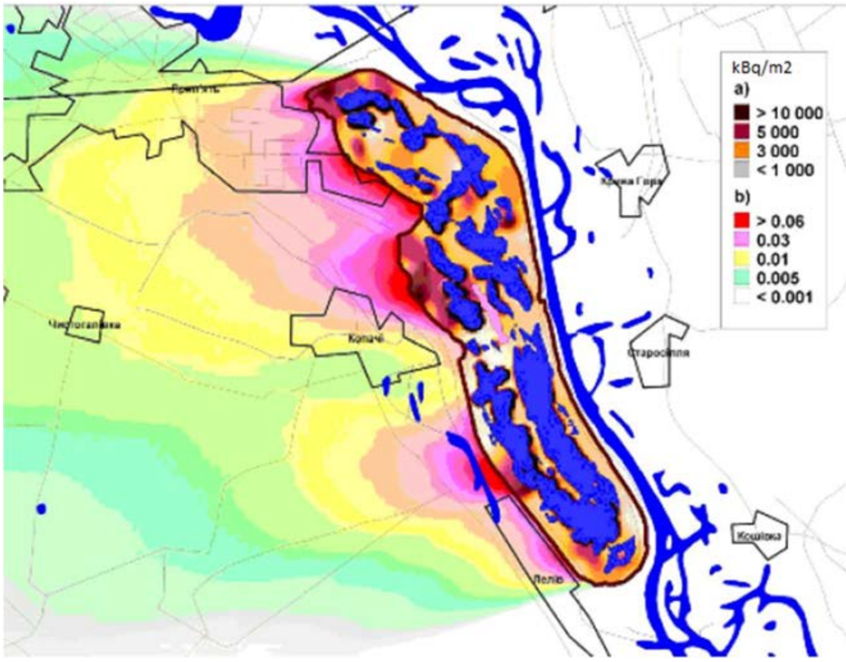


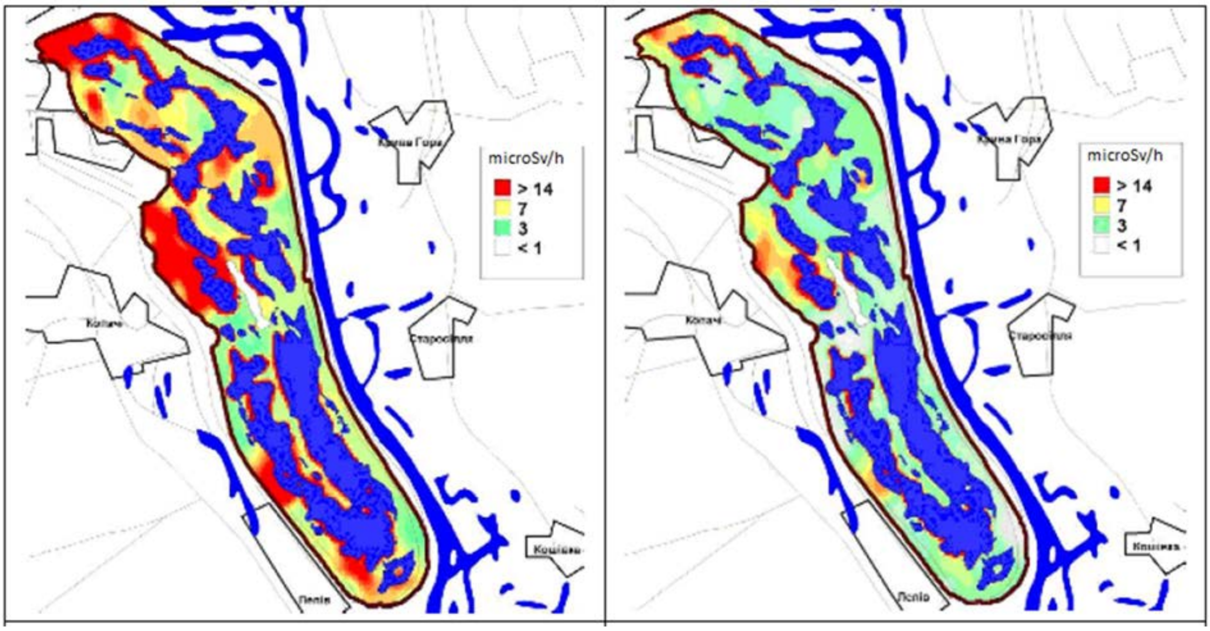
FIG. 48. Additional contamination of land by ^{137}Cs due to atmospheric transport of radioactivity in case of dry grassland fire on drained bottom of the pond , for wind direction towards ChNPP: a) surface contamination density of the drained area of the pond; b) surface contamination density of the surrounding territory (based on data [75]).

4.4. EXTERNAL DOSE RATES FROM THE DRAINED BOTTOM SEDIMENTS

Following the water level drawdown in the pond, the drained bottom sediments will represent the source of potential external exposure for the staff of the ChNPP and adjacent facilities.

Estimation of the external gamma dose rate at the drained bottom of the cooling pond at 1 m height above soil surface was carried out in [75]. The bottom sediment contamination maps described in section 3.2.3 were used as input data for dose calculations. Results are shown in FIG. 49. Two models assuming different types of vertical activity distribution in bottom sediments based on dose conversion coefficients developed in [84] were used in dose assessment. The first most conservative model assumed that activity inventory is contained in the surface layer of bottom sediments (FIG. 49A). The second model more realistic model assumed that activity inventory is homogeneously distributed in the upper 5 cm layer of bottom sediments (FIG. 49B).

Based on calculations, the highest external dose rates from bottom sediments are expected in the northwest part of the drained pond bottom and in the area close to the mouth of the outflow channel of the cooling pond. It was expected that in most highly contaminated areas of the drained pond bottom carrying out of remedial measures may be warranted [75].



(A) External dose rate for model of surface activity distribution

(B) External dose rate model for model of activity distribution in 5 cm layer

FIG. 49. Estimated distribution of external gamma dose rate in the drained cooling pond bottom at 1 m height above soil (based on data [75])

4.5. INCREASED MOBILITY OF RADIONUCLIDES IN THE DRAINED BOTTOM SEDIMENTS

As discussed in section 3.2.4, the ^{90}Sr, ^{241}Am and Pu isotope activity inventory in bottom sediments of the cooling pond based on studies conducted in 1999 – 2012 was mostly associated with the undissolved nuclear fuel particles [6, 16, 19, 29, 34, 37].

Low solubility of fuel particles in the bottom sediments of the cooling pond was attributed to anoxic conditions caused by oxidation of organic matter in bottom sediments [6, 34, 37].

It was expected that as a consequence of water level drawdown in the pond the dissolution rate of fuel particles in the exposed to atmosphere bottom sediments may increase significantly due to access of atmospheric oxygen, as well as due to acidification of soils due to biogeochemical process in the exposed sediments [6, 29, 34, 37] .

Bulgakov et al. [34] predicted the acidification rate of the drained sediments from literature data on the decrease of soil pH in time after soil liming. Based on these studies significant increase of fuel particle dissolution in exposed to atmosphere sediments of the pond compared to the flooded sediments rate was predicted (FIG. 50).

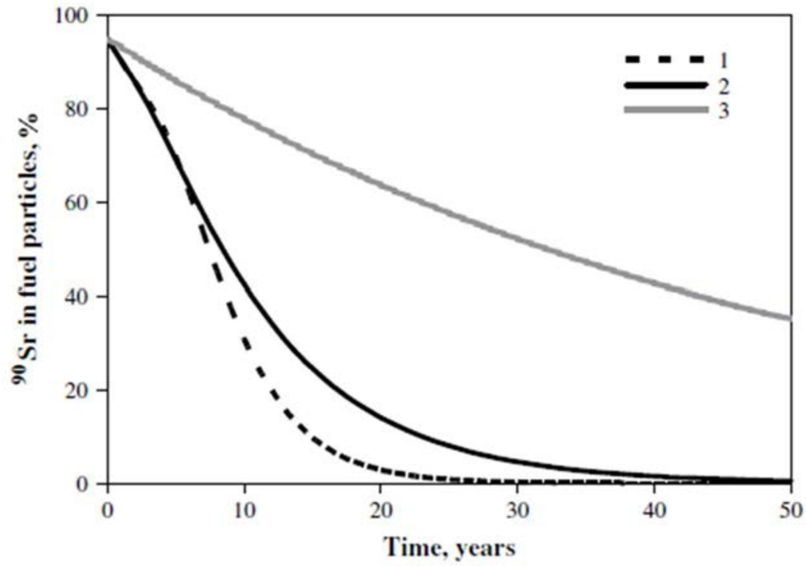


FIG. 50. Prediction of ^{90}Sr fraction remaining in fuel particles as a function of time after a reduction of water level in the cooling pond. 1 – exposed sediments of the main part of the pond; 2 – exposed sediments of the pond part adjacent to the ChNPP; 3 – flooded sediments [34].

Possibility for the increased release rate of radionuclide release to mobile chemical forms from bottom sediments of the pond was considered as a factor, which may cause increased transfer of radioactivity to the vegetation, as well as to promote radionuclide transport in groundwater to the Pripyat River.

4.6. INFLUENCE OF THE COOLING POND WATER LEVEL DRAWDOWN ON RADIONUCLIDE TRANSPORT TO PRIPYAT RIVER AND HYDROGEOLOGICAL CONDITIONS AT THE CHNPP SITE

4.6.1. Radionuclide transport in groundwater to Pripyat River

4.6.1.1. Changes of hydrodynamics of groundwater flow in the course of the water level drawdown in the pond

In order to forecast radionuclide migration process in groundwater in conditions of water level drawdown in the pond, it is important to understand the corresponding changes in groundwater flow hydrodynamics.

To analyze groundwater flow patterns in the course of water level drawdown in the pond Bugai and Skalskyy [41] used the 2D cross-sectional groundwater flow model describing the seepage process in the system "cooling pond-drainage ditches-Pripyat / Glinitsa Rivers". This model encompasses geological cross-section, which is oriented in perpendicular direction to the pond axis with the total horizontal extension of 2600 m (FIG. 51).

The groundwater flow model incorporates (from top to bottom) the unconfined aquifer in the Quaternary alluvial deposits, the Eocene marl aquitard layer and Eocene confined aquifer in sandy deposits (see section 2.2.2 for details on site hydrogeology). The groundwater flow model was developed using the Visual Modflow software [73].

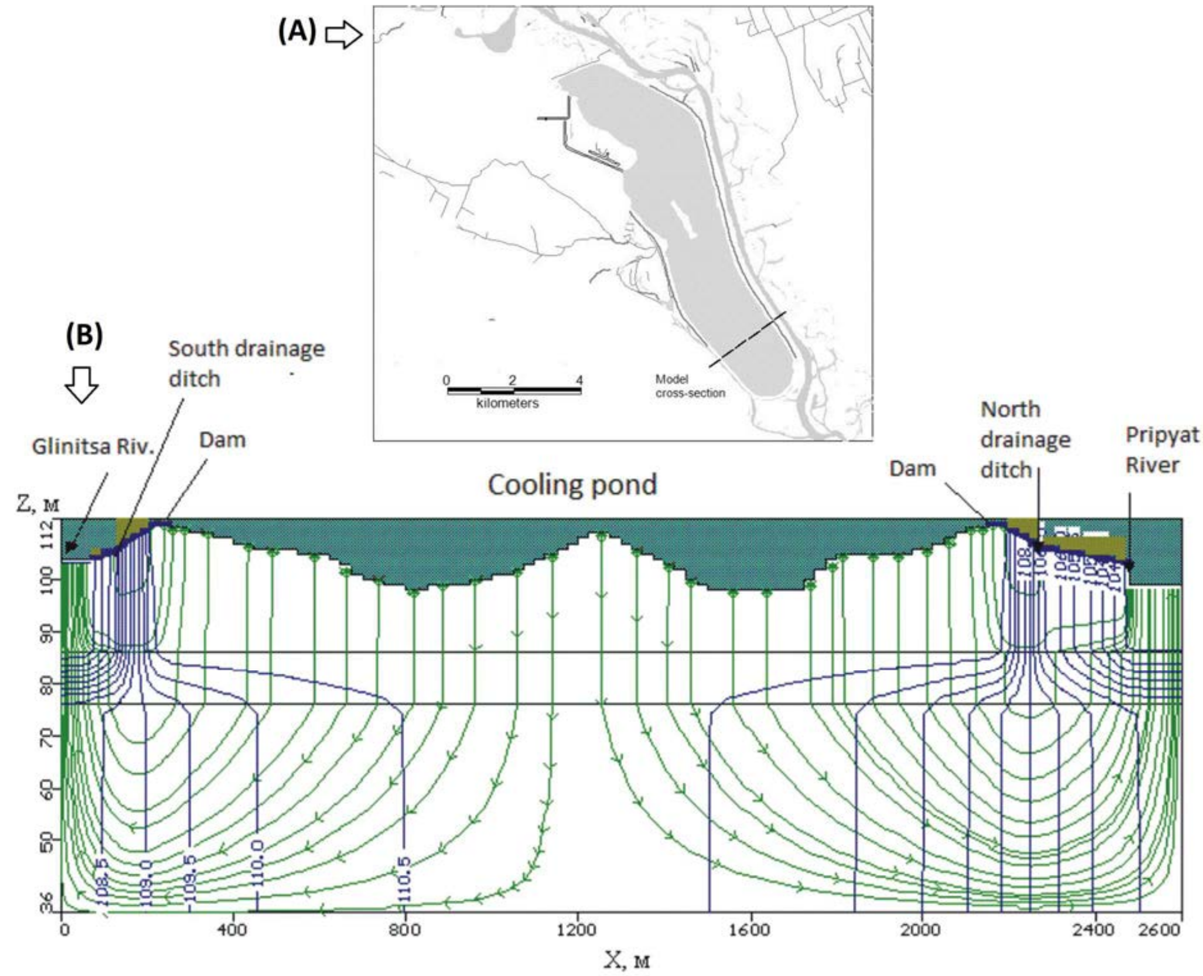


FIG. 51. 2D cross-sectional model describing groundwater flow process in the system "cooling pond – drainage ditches – Pripyat River / Glinitsa River". (A) - Position of model cross-section; (B) - The flow net in the model domain (hydraulic head isolines in blue color and flow path lines in green color) corresponding to the water level in the pond H=110.8 m a.s.l. (based on data [41]).

Illustrative groundwater flow calculations were carried for three values of water level in the cooling pond: 110.8 m a.s.l. (operating water level), 106 m a.s.l. (intermediate level in the pond in the process of level drawdown) and 104.7 m a.s.l. (long-term level in the residual lake following the pond drainage, which is close to "equilibrium" condition, see section 4.2). Results of calculations are summarized in TABLE 24 and TABLE 25.

Evolution of hydrodynamic conditions during water level drawdown in the pond is governed by the two key factors: (1) diminishing of the hydraulic head difference between the pond and drainage contours (Pripyat and Glinitsa Rivers), and (2) the retreat of the shoreline of the pond, and increase in distance between the contracting pond and drainage contours.

The retreat of the shoreline of the pond can be illustrated by the following numerical values: for the water level in the pond H_p=110.8 m average distance to Pripyat River is 270 m; for water level in the pond of 106 m distance to Pripyat increases to 450 m; for water level in the pond of 104.7 m distance to Pripyat reaches 570 m (for the considered pond cross-section).

TABLE 24. DEPENDENCE OF SEEPAGE LOSSES FROM WATER LEVEL IN THE COOLING POND (*based on data* [41])

Water level in the pond, m a.s.l.	Water ex-filtration per 1 m of dam length, m^2/day			
	Pripyat River (103.4 m a.s.l.)	North drainage ditch (106.2 m a.s.l.)	Glinitsa River (104 m a.s.l.)	South drainage ditch (105.5 m a.s.l.)
110.8	4.2	8.1	6.1	7.8
106	1.6	NA	1.3	NA
104.7	0.75	NA	0.47	NA

As result, significant decrease in seepage losses from the pond to Pripyat River occurs in the process of pond level drawdown (i.e. by a factor of ≈10 for H_p=106 m.a.s.l., and by a factor of ≈20 for H_p=104.7 m a.s.l.; see TABLE 24). In parallel, groundwater seepage velocities are decreasing and groundwater transit times from the cooling pond to Pripyat and Glinitsa Rivers are increasing. In particular, water transit time from pond to rivers increases from 2 months (for pond operating conditions) to 20–40 years (for the pond level of 104.7 m a.s.l.) (see TABLE 25).

Respectively, significant decrease in activity fluxes in groundwater and increase of radionuclide travel times in subsurface from the cooling pond to river network can be envisaged [41].

TABLE 25. DEPENDENCE OF GROUNDWATER FLOW VELOCITIES FROM THE COOLING POND TO DISCHARGE CONTOURS FROM THE WATER LEVEL IN THE POND (*based on data* [41])

Water level in the pond, m a.s.l.	Groundwater flow pore velocity , m/year (travel time of groundwater is given in parentheses)			
	Pripyat River (103.4 m a.s.l.)	North drainage ditch (106.2 m a.s.l.)	Glinitsa River (104 m a.s.l.)	South drainage ditch (105.5 m a.s.l.)
110.8	162 m/year (20 months)	420 m/year (2 months)	195 m/year (8 months)	420 m/year (2 months)
106	64 m/year (7 years)	NA	54 m/year (7 years)	NA
104.7	25 m/year (23 years)	NA	13.5 m/year (37 years)	NA

4.6.1.2. *Assessment of radionuclide migration in groundwater from the drained bottom sediments to Pripyat River*

In case of draining of bottom sediments of the cooling pond the changing and more aggressive bio and geochemical environment (better oxygen access, acidification of sediments etc.; see section 4.5) can promote higher dissolution rates of fuel particles contained in bottom sediments and subsequent radionuclide migration to groundwater.

Conservative assessment of radionuclide transport in groundwater from the drained bottom sediments was carried out in [41]. The modeling employed the NORMALYSA (NORM and LegacY Site Assessment) tool (http://project.facilia.se/normalysa/software.html) [85] based on the Ecolego 6 software platform (http://ecolego.facilia.se/ecolego/show/Software).

Calculations were carried out for ^{90}Sr, which is the radionuclide of primary concern for groundwater pathway (see section 3.4.1.2). The general schematization of radionuclide migration in groundwater from the drained bottom sediments of the cooling pond to Pripyat River is shown in FIG. 52. The figure shows a schematic cross-section of the aquifer between the residual lake and Pripyat River. It is assumed that radionuclides from contaminated bottom sediment layer infiltrate through the unsaturated zone to the aquifer and are transported by horizontal flow in the aquifer towards Pripyat River.

To model release of radioactivity from the drained bottom sediments, the radionuclide soil leaching model described in [86] was used. This model assumed that all radionuclide inventory contained in the contaminated soil (bottom sediment) layer was in the mobile (exchangeable) form. Radionuclide transport in the unsaturated zone and aquifer was modeled using the advection-diffusion equation taking into account radionuclide sorption by soil matrix (using the Kd model) and radioactive decay.

The following conservative values of ^{90}Sr Kd values were used in groundwater transport calculations: 10 l/kg for bottom sediments, and 1 l/kg for soils of the unsaturated zone and aquifer. The infiltration rate of 0.2 m/year was assumed, which is a typical value for Pripyat River floodplain areas [69].

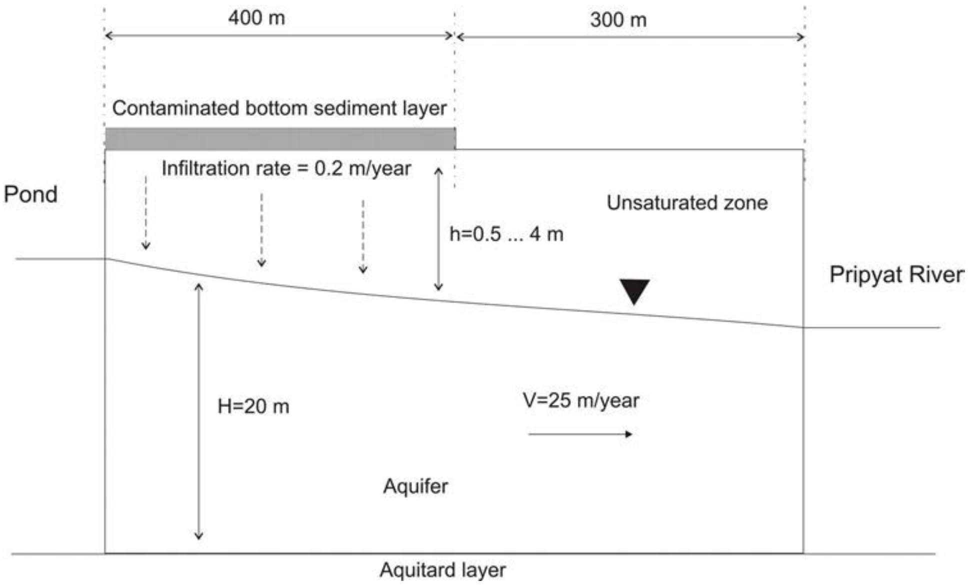


FIG. 52. Schematization of of ^{90}Sr transport in groundwater from the drained bottom sediments of the cooling pond to Pripyat River (based on data [41]).

The bottom area of the pond was subdivided into a set of compartments in accordance with contamination densities of the bottom sediments by ^{90}Sr (ranging from 3.7×10^5 to 9.3×10^5 Bq/m^2) and thickness of the unsaturated zone. Results of calculations are shown in FIG. 53.

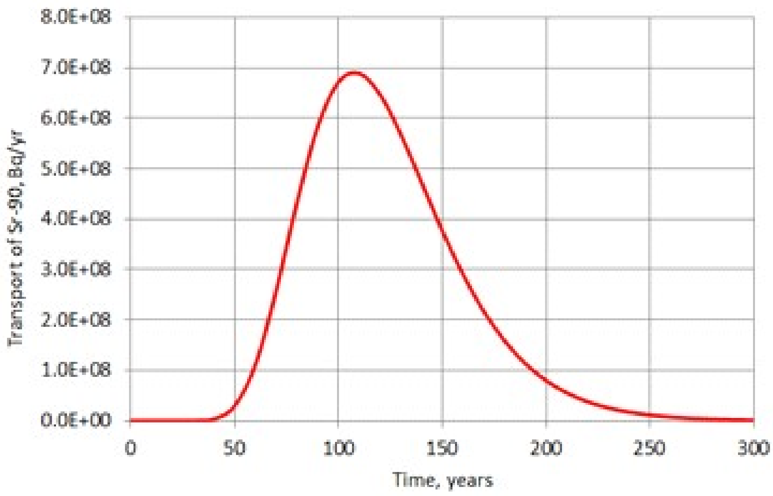


FIG. 53. Conservative modeling prediction of ^{90}Sr transport in groundwater from the drained bottom sediments to Pripyat River (based on data of [41]).

The maximum ^{90}Sr transport to Pripyat River from the drained bottom sediments was predicted to occur at t=110 years following the pond drainage, and the maximum activity flux of ^{90}Sr was estimated at 0.7 GBq/yr. This is less than 0.3% of the estimated ^{90}Sr transport from the cooling pond to Pripyat River in 2010 (see section 3.5.1).

4.6.1.3. *Calculations of radionuclide transport from the residual lakes within the cooling pond bottom to Pripyat River*

Calculations of radionuclide transport from residual lakes situated within the cooling pond bottom to Pripyat River were carried out in [41]. The groundwater transport analyses employed the NORMALYSA software tool, and modeling methodology was similar to the methodology described in the previous paragraph.

Assuming that fuel particles contained in bottom sediments in the residual lakes will dissolve with the rate of ≈0.016 yr^{-1} (i.e. 1.6% of inventory per year) and released ^{90}Sr to water column, the maximum ^{90}Sr activity concentration in the water of residual reservoirs was conservatively estimated at 40 to 70 Bq/l. (The above value dissolution rate constant was estimated from ^{90}Sr balances in the water of the cooling pond in 2000–2012; similar range of values was reported by [34]). This value was further used as a source concentration to model radionuclide transport in groundwater to Pripyat River.

Based on conservative groundwater transport analyses maximum ^{90}Sr transport from residual lakes to Pripyat River will be less than 3.2 GBq/yr. This is less than 1.2 % of the estimated ^{90}Sr transport from the cooling pond to Pripyat River in 2010 (see section 3.5.1).

Therefore, it can be concluded that radioactivity sources in the drained bottom sediments of the cooling pond and in the bottom sediments of the residual lakes do not pose significant risk for radioactive contamination of Pripyat River [8, 41].

4.6.2. Influence of the cooling pond drawdown on hydrogeological conditions of the adjacent hazardous sites and facilities

Water level drawdown in the cooling pond is expected to influence significantly the hydrogeological conditions (groundwater levels and flow patterns) in the vicinity of the pond. After decommissioning of the pond, the hydrogeological conditions will evolve towards natural conditions, which existed at the site before the construction of the ChNPP.

Discussion of the impact of drainage of the pond on hydrogeological conditions at ChNPP site presented below is based on modeling analyses utilizing the regional groundwater flow model of the Chernobyl Exclusion Zone (see section 4.2.1) carried out in [41].

Estimated values of groundwater level drawdown for specific objects (“Sarcophagus”, radioactive waste disposal and storage sites) are summarized in TABLE 26. Description of the discussed above radiation-hazardous objects is given in section 3.7.2. Predicted aerial distribution of groundwater level drawdown in the unconfined aquifer in the vicinity of the cooling pond due to pond drainage is shown in FIG. 54.

The maximum decrease of groundwater level is predicted at the Industrial site of ChNPP and at the RWDS “3rd Stage of ChNPP” (1.7–5 m). As a result, the hydrogeological conditions at “Sarcophagus” site are expected to improve, and infiltration of groundwater to the basement premises of ChNPP is expected to decrease (see section 3.7.2).

The radioactive waste storage conditions in the repository “3rd Stage of ChNPP” are also expected to improve, and the groundwater level is predicted to decrease below the basement of this facility (it should be reminded that this storage facility was party flooded by groundwater during the post-accident period; see section 3.7.2).

Groundwater flow directions are expected to change. While in conditions before the drawdown of the water level in the pond the main groundwater discharge contour was Pripyat River, in newly established conditions the discharge contours in many cases will be residual lakes within the cooling pond bottom.

On the whole, water level drawdown in the cooling pond is expected to provide positive influence on protective capacity of local hydrogeological environment with regard to radioactive materials stored in the near-surface disposal and storage facilities at ChNPP site. First, the thickness of the unsaturated zone will increase throughout the site (FIG. 54). Second, the transit times of radioactive contaminants from the residual lakes towards Pripyat River will increase while the activity fluxes in groundwater will be much lower compared to the conditions which existed before the pond d rawdown [41].

TABLE 26. ESTIMATED DRAWDOWN OF GROUNDWATER TABLE FOR RADIOACTIVELY HAZARDOUS SITES IN THE VICINITY OF CHNPP FOLLOWING THE DRAWDOWN OF WATER LEVEL IN THE COOLING POND (*based on data* [41])

Object / Site	Decrease of groundwater level, m
“Sarcophagus”	1.7 –4.0
RWDS “3rd Stage of ChNPP”	1.7 –5.0
RWTSP “Yanov Station”	0.2 –0.5
RWTSP “Red Forest”	0.2 –0.5
RWTSP “Staray Stroybaza”	0.5 –1.0
RWTSP "Novaya Stroybaza"	0.5–4.0

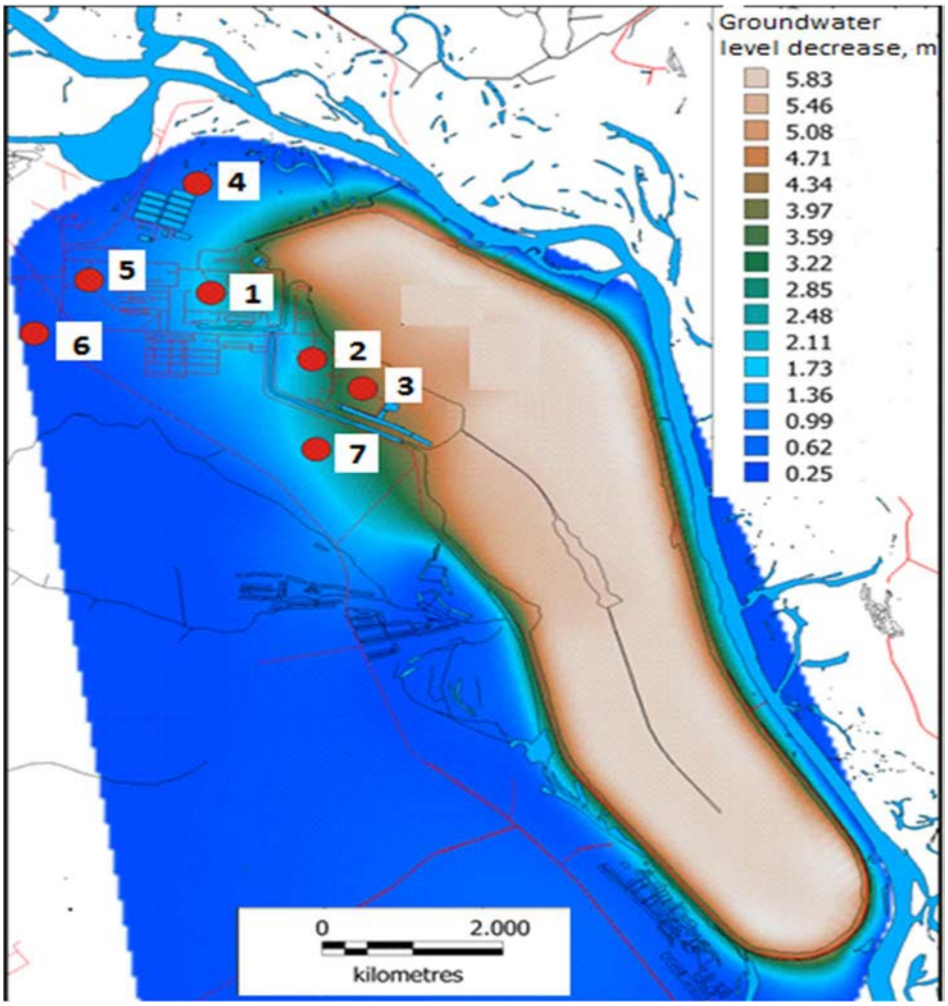


FIG. 54. Predicted drawdown of groundwater levels in the unconfined aquifer in Quaternary deposits following the drawdown of water level in the cooling pond for the "normal" climatic scenario: 1-Sarcophagus; 2-industrial site of the 3rd Stage of ChNPP; 3-RWDS "3rd Stage of ChNPP"; 4-RWDS "Podlesny"; 5-RWTSP "Starya Stroybaza"; 6-RWTSP "Red Forest"; 7-RWTSP "Novaya Stroybaza"(based on data [41]).

4.7. CONSEQUENCES OF COOLING POND ECOSYSTEM TRANSFORMATION

The water surface of the pond was predicted to decrease to some ≈30% of the initial cooling pond area under 'normal" climatic conditions scenario, and to approximately to ≈25% of the initial pond area under "dry" conditions scenario (see section 4.2). The water level drawdown induces changes in the depth, morphology, water exchange rate, hydro-chemical and temperature regimes of the residual lakes.

Thus, the decline of the water level in the cooling pond was expected to cause a significant impact the aquatic ecosystem of this water reservoir [6, 8, 25]. In particular, the dying out and/or essential reduction of a number of some aquatic species has been envisaged.

Some authors were concerned that perishing of a large amount of biomass and decomposition of the resulting organic substances may have potential negative impact on the water quality of residual reservoirs (especially in conditions of a fast uncontrolled decline of the water level in the pond) [6, 20, 25].

4.7.1. Effects on water quality

SMITH et al. [6] disputed that increased biomass density in new lakes will lead to more intensive production of ammonia, especially in the bottom sediments, where the ammonia increase up to concentrations typical for eutrophic lakes was predicted. The growth of ammonium concentration could provoke increase in potassium (i.e. competitive ion for ammonium in bottom sediments) in the water column. Growth of ammonium concentration in bottom sediments along with decrease of self-purification (due to stopping pumping water from Pripyat River and decreased ex-filtration) were predicted to cause increase of ^{137}Cs activity concentration in water of the residual lakes. Decrease in self-purification rate of lakes was also expected to cause gradual increase of ^{90}Sr activity concentration in water.

The report of IHB [25] points to likely influence on water quality of the decomposition of 'excessive' organic materials in residuals lakes, which was expected to cause lowering of oxygen concentration in water column. In addition, the thermal regime of the newly formed lakes is expected also change due to faster heating and higher temperatures of water in spring-summer period (caused by a smaller volume and depth of reservoirs) and due to faster cooling in autumn-winter period.

4.7.2. Effects on higher aquatic vegetation and phytoplankton

According to assessment of IHB [25], the retreat of the pond shoreline will cause the substantial reduction of higher aquatic vegetation (emergent and submerged species), and the dying out of phytoperiphyton on stone heaps and claddings, which were present in the near-shoreline area of cooling pond under the operating water level.

Higher aquatic plants are mostly widespread up to depths of 2.5–3.0 m. It is expected that during the initial period of water level drawdown by 2.0–2.5 m majority of submerged water plants on drained territories will die out. The decreasing of the water level and retreat of shoreline will likely affect, in the first place, emergent plants (the common reed). The majority of these plants however will likely re-populate the shoreline of newly formed lakes [6, 25].

Water level drawdown in pond will facilitate faster heating of water masses in residual lakes, and this may under certain circumstances promote development of blue-green algae. As already discussed, additional inflow and decomposition of organic substances in water strata may cause increase of mineral forms of nitrogen (NO_2^-, NO_3^-, NH_4^+) and dissolved inorganic phosphorus. Overall, it may cause intensification of photosynthesis processes and increasing of phytoplankton biomass [25].

Changing hydro-chemical and thermal conditions in the reservoir may cause succession of higher aquatic plants and phytoplankton, dominated by species most adapted to new conditions. The regime of production of phytoplankton in residual reservoirs is expected to stabilize during 3–4 years after the formation of a quasi-steady state water regime of newly formed reservoirs [25].

4.7.3. Effects on zoo-benthos

The retreat of the shoreline of the cooling pond will affect a substantial part of zoo-benthos such as mussels attached to solid substrates (stone heaps and cladding). According to studies of IHB [25] > 95% of zoo-benthos biomass inventory in the cooling pond was formed by *Dreissena* mussels.

A substantial part of *Dreissena* on drained territories will die out, as they will be unable to migrate fast enough to keep with the declining water level in the pond. In addition, the shoreline and bed of residual reservoirs will be formed of sandy deposits, which are not a suitable habitats for *Dreissena.* Therefore, a major decline in *Dreissena* and other zoo-benthos species associated with *Dreissena* was expected [6, 25].

According to estimates of IHB [25], the drained territories may contain up to ≈6,300 tons of organic substances formed due to dying-out of zoo-benthos and zoo-periphyton: ≈1,600 tons at depths up to 3 m, and ≈4,600 tons at depths of 3–6 m (TABLE 27).

In case the discussed above organic materials will be washed to the newly formed lakes, this may significantly affect nutrient balance and oxygen content in water column [6].

TABLE 27. ESTIMATED AMOUNT OF ORGANIC SUBSTRATE OF ZOO-BENTHOS AND ZOO-PERIPHYTON (WET WEIGHT) WITHIN THE DRAINED AREA OF THE COOLING POND (*based on data* [25])

Depth range	Zoo-benthos, tones	Zoo-periphyton, tones	Sub-total, tones
1–3 m	400	1217	1617
3–6 m	4677	NA	4677
Total	NA	NA	6294

4.7.4. Effects on macroinvertebrate community

The potential effects of cooling pond ecosystem transformation due to level drawdown on macroinvertebrate aquatic species community have been analyzed in [6]. The residual lakes will be much smaller and have much lower water exchange rate. There will be likely less wave action in these lakes, and a more suitable littoral zone (lake margin areas), which will form a better a habitat environment for macroinvertebrates. Therefore, the diversity of aquatic macroinvertebrates in the newly formed lakes is expected increase compared to conditions in the cooling pond before the drainage. SMITH et al. [6] envisaged an eventual increase in mean taxon richness from 23 (as in 2005) to around 40–50 species.

4.7.5. Effects on fish

When operated, the cooling pond had a much higher diversity of fish species than other, smaller lakes in the area due to its greater area, as well as (in the past) due to the inflow of heated water [6].

It was expected that following the water level drawdown in the pond both population sizes, and number of fish species in the newly-formed lakes will decline dramatically [6, 25].

The factors which were expected to influence fish population include:

- decrease in the nutritive base of fishes due to contracting littoral areas;
- reduced suitable spawning areas;
- deterioration of oxygen regime;
- greater competition between individuals of a species, and between different species (in smaller lakes);
- following the cessation of water inflow to the pond, fish which need running water for reproduction will decline.

Fish dying-out caused by low dissolved oxygen during the summer and winter periods will be likely more frequent.

Therefore, because of the discussed above changes, the number of fish species in the pond could be reduced from 40 (as in 2005) to as few as 22–25. There is a high probability of loss of two endangered species (the Ukrainian lamprey, *Eudontomyzon mariae*, and the Undermouth *Chondrostoma nasus*) which currently appear in the Red Book of rare species of Ukraine [6].

5. DECOMISSIONING AND REMEDIATION STRATEGY

5.1. COMAPRISON OF THE CONTROLLED VS. ‘NATURAL’ REGIMES OF POND WATER LEVEL DRAWDOWN

As discussed in section 4.1, drawdown of water level in the pond has been identified in a sequence of pre-design research projects and feasibility studies as an ultimate option for the Chernobyl pond decommissioning [1–8].

Risk assessment analyses of consequences of cooling pond level drawdown reviewed in section 4 of this report has shown that:

- Even conservative scenarios related to atmospheric resuspension of contaminated bottom sediments result in very low secondary contamination levels of surrounding territory and low inhalation doses to the reference persons (below levels of concern) (section 4.3.1);

- Same conclusion applies to scenario of the wildfire of the dried-up vegetation growing on the contaminated bottom sediments in the drained areas of the pond (section 4.3.2);

- Though the radionuclide mobility in the exposed bottom sediments may increase following the pond level drawdown due to dissolution of fuel particles (see section 4.5), the predicted ^{90}Sr transport to Pripyat River will decrease by at least by a factor of $\sim \times 100$ (compared to the situation before the pond level draw-down) due to changed boundary conditions (section 4.6);

- On a whole, water level drawdown in the pond was expected to provide positive influence on hydrogeological conditions of Sarcophagus and adjacent radioactive waste disposal and storage sites (section 4.6.2).

The potential negative consequences of the cooling pond drawdown included possibilities for creation of some local ‘hot spots’ of highly contaminated bottom sediments with the elevated gamma dose rate in drained areas in the northern part of the pond and near mouth of the outflow channel (section 4.4).

The issue of concern was also ‘ecological risk’ related to possibility of dying out of large amounts of biomass of aquatic organisms, and resulting negative effects of decomposition of the organic substances on water quality of the residual lakes (section 4.7).

Thus, risk assessment studies has confirmed that drawdown of level in the pond is generally acceptable in terms of radiological safety and advantageous with respect to a number of important considerations (e.g. hydrogeological aspects; radionuclide transport to Pripyat River) strategy for decommissioning of the pond. However, identified risks of potential negative radiological and ecological consequences have to be continuously monitored and properly managed in the course of pond level drawdown.

The latest cooling pond decommissioning strategy feasibility analyses [7, 8] have further compared advantages and disadvantages of decommissioning options of carrying cooling pond level drawdown in (1) a 'natural mode', or (2) 'controlled mode'

The 'natural mode' of pond drainage assumes that water level drawdown in the pond decreases under influence of only 'natural' environmental factors such as seepage losses and evaporation losses.

The 'controlled mode' (or 'staged mode') assumes that water level in the pond is lowered in a sequence of intermittent intervals. In between level drawdown intervals, the water level in pond is maintained by means of pumping station, allowing for monitoring, assessment of conditions in the pond, and taking corrective remedial actions, if needed (FIG. 55).

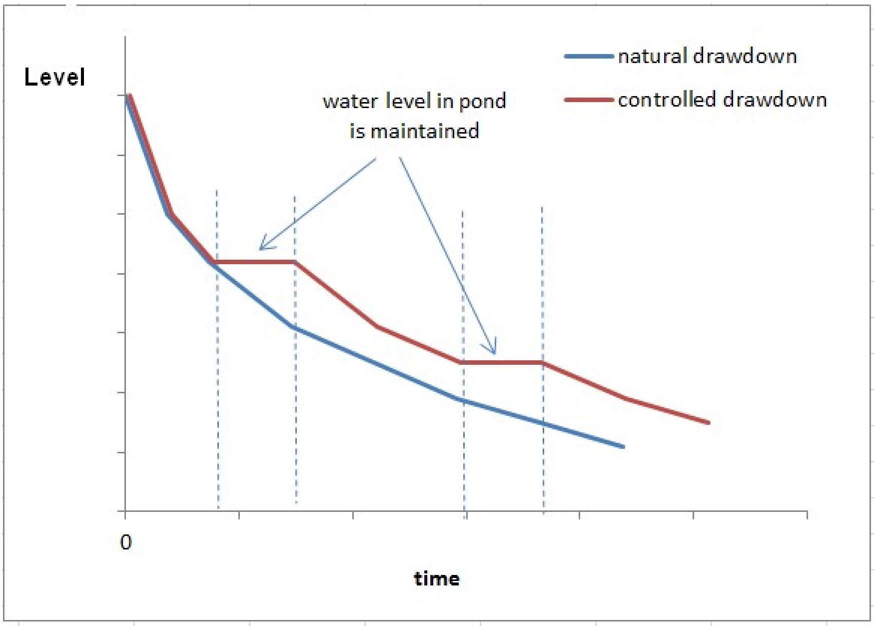


FIG. 55. Scheme of water level drawdown in cooling pond in 'natural' and 'controlled' modes.

Comparison of listed above options of 'natural' and 'controlled' water level drawdown in the cooling pond is provided in TABLE 28.

The 'natural' level drawdown was a technologically simpler and cheaper option for implementation. However, this option entailed higher potential risks of negative ecological and, possibly, radiological consequences.

On the other hand, 'controlled' level drawdown (though more costly) was a more flexible and risk-free cooling pond decommissioning option. In this case, the water level drawdown was supposed to proceed in a sequence of stages, where the rate and duration of each next stage should have been adjusted based on monitoring results and experience of the previous stage.

Therefore, the IPS NPP [8] concluded that the is the preferred decommissioning strategy for the pond.

The recommended controlled water level drawdown rate aimed at minimization of "ecological risks" (i.e. dying out of aquatic species and deterioration of water quality due to decomposition of organic matter) was ~1 m per year during first 2 years of cooling pond decommissioning; it was advised that the water level drawdown should start in early spring in conditions of relatively low surface water temperature and good oxygenation of pond water column [8].

TABLE 28. COMPARISON OF DIFFERENT OPTIONS FOR WATER LEVEL DRAWDOWN IN THE COOLING POND IN THE COURSE OF ITS DECOMMISSIONING (*based on data* [8])

Pond level drawdown scenario	Positive features	Negative features
Natural level drawdown	Lowest implementation costs No need to maintain/repair dam and pumping station Technologically most simple Minimizes impact on radioactive contamination of Pripyat River	Ecological risks of "excessive biomass" dying out Risk of slower than expected biological succession of drained territories Possibility of unforeseen radiological and ecological factors/risks Economic risks of costly remedial measures to mitigate potential negative consequences
Controlled level drawdown	Creates better conditions for natural attenuation process in the drained areas Minimizes risks of negative radiological and ecological consequences Allows for implementation of corrective actions, if needed, and revision of strategy	Higher operational costs (electricity costs for operation of pumping station, staff salaries, dam repairs etc.) Risk of dam failure Continued radionuclide transport to Pripyat River

The decommissioning strategy for the pond developed in [8] foresaw carrying out, if necessary, additional remedial measures to liquidate the possible activity "hot spots" within the drained pond bottom area, not complying with the established end-state radiological criteria.

The end-state criteria for the pond and possible remedial measures for contaminated bottom sediments are discussed in the following paragraphs of the report.

5.2. THE END-STATE RADIOLOGICAL CRITERIA FOR THE COOLING POND DECOMISSIONING

5.2.1. Regulatory framework for the cooling pond decommissioning

The activity on decommissioning of the cooling pond of ChNPP was very specific, and there was evidently a lack of Ukrainian normative documents for formally regulating various aspects of this activity [8]. One particular difficulty is that the cooling pond is situated within the territory of the Chernobyl exclusion zone with high background radioactive contamination levels by Chernobyl fallout.

Therefore when developing the project design for cooling pond decommissioning, the design institute IPS NPP referred to the relevant IAEA guidance documents and recommendations on decommissioning of nuclear facilities and remediation of radioactively contaminated sites [87–91]. At the initial stage of the cooling pond decommissioning, the Chernobyl NPP (operator of the pond) has approved with the relevant Ukrainian regulatory authorities (Ministry of Health (MHU) and State Nuclear Regulatory Inspectorate of Ukraine (SNRIU)), so called “Technical Decision” document [92], which defined the critical events and scenarios, which needed to be evaluated in the EIA analyses, as well as the end-state radiological criteria for the cooling pond decommissioning project.

5.2.1.1. Objective of cooling pond decommissioning

The *objective* of the Chernobyl NPP cooling pond decommissioning is defined in [8] as: “Safe completion of its (cooling pond) exploitation as a ‘technological object’ of the NPP; lowering of water level in the reservoir as a consequence of natural process of filtration and evaporation. The aim is also to support conditions for natural rehabilitation (restoration) of the transformed ecosystem within its area. The radiological impacts from the transformed ecosystem of the cooling pond following decommissioning shall not differ from radiological impacts from surrounding territories (contaminated as a result of Chernobyl accident)”.

It was expected that as a result of decommissioning of the cooling pond due to natural drainage of water from the reservoir the following conditions will be met [92]:

- There will be no need to allocate financial resources for exploitation of the cooling pond as a technological reservoir;

- The risks related to the failure of the dam of the pond will be eliminated;

- Radioactivity fluxes from the pond by water pathway to Pripyat River will be efficiently reduced;

- The groundwater levels in surrounding territories will decrease, which will lower risks of radionuclide migration to groundwater from the adjacent radioactive waste disposal and storage sites.

5.2.1.2. Restricted site release concept

The cooling pond is situated in so called "near zone" of ChNPP, which is characterized by high levels of radioactive contamination by Chernobyl fallout. The Law of Ukraine on the Chernobyl Exclusion zone [93] does not foresee carrying out decontamination or cleanup of this territory, and in fact, this law establishes the regime of restricted usage of this territory.

Therefore, it was appropriate to apply the strategy of restricted usage/release to the cooling pond decommissioning [8].

5.2.1.3. Critical events and scenarios to be considered in EIA report for cooling pond decommissioning

The "Technical Decision" document [92] has coordinated with the regulatory authorities that the critical events to be considered in EIA of the cooling pond decommissioning project design should include:

- Scenario of atmospheric resuspension and transport of the dried up bottom sediments of the pond under normal and unfavorable meteorological conditions, and
- Scenario of atmospheric transport of radioactivity in case of wildfire of the dry contaminated vegetation growing on the drained pond bottom.

The parameters for these scenarios (e.g. AMAD of radioactive aerosols, resuspension coefficient values, meteorological parameters, etc.) were also coordinated with the regulatory authorities. The discussed values of parameters correspond to parameter values listed in section 4.3 of this report.

5.2.2. End state radiological criteria

The "Technical Solution" document [92] established the end-state radiological criteria for the cooling pond based on the following considerations.

There are no plans in place for the cleanup of the territory of the Chernobyl Exclusion Zone in order to bring it to the unrestricted use, even after decommissioning of the Units 1, 2 and 3 of the ChNPP. Therefore, it was reasonable to set the end state radiological criteria for the decommissioning of the cooling pond, which were similar to the existing radiation safety criteria in the Chernobyl exclusion zone.

The programme for decommissioning of the ChNPP [94], which was approved by Ministry of Emergencies and coordinated with the MHU and SNRIU, has defined the end state of ChNPP as a "brown field". The end-state radiation parameters for the decommissioning of ChNPP were further précised in the document [95], which has established the following gamma exposure dose rate (EDR) end-state criteria:

- The EDR value for 2012 was established as 14 μSv/hour for the "zone of enhanced regime" (i.e. highly contaminated industrial site of ChNPP with the restricted access), and 7 μSv/hour for the “zone of free regime” (i.e. zone adjacent to ChNPP with the same access regime as the 10km zone of ChNPP).

The existing ‘control levels’ of volumetric activity of radionuclides in the air of the Chernobyl Exclusion zone in accordance with the document [96] are listed in TABLE 29.

TABLE 29. CONTROL LEVELS OF VOLUMETRIC ACTIVITY OF RADIOACTIVE AEROSOLS IN THE AIR OF CHERNOBYL EXCLUSION ZONE (*based on data*[96])

Radionuclide	Control volumetric activity concentration, Bq/m^3
^{90}Sr	3.0×10^{-3}
^{137}Cs	1.0×10^{-2}
Transuranic radionuclides (sum of ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Am)	2.0×10^{-3}

The gamma dose exposure rate is an easy to measure parameter, which also correlates with the surface contamination density by ^{137}Cs. Contamination densities of bottom sediments by other radionuclides usually show good correlation with ^{137}Cs (see section 3.2.2). Radioactive aerosol activity concentrations in the air also usually correlate with soil surface contamination levels. Therefore the criteria formulated in the form of gamma dose exposure rate levels were defined (and coordinated with regulatory authorities) as the main end-state radiological criteria for the decommissioning of the cooling pond [92]. These criteria were coherent with the discussed above general end-state criteria for decommissioning of the ChNPP.

For the higher contaminated “Northern sector” (Zone 1) of the cooling pond the end-state criterion was set as 14 μSv/hour; for the less contaminated “Southern sector” (Zone 2) of the pond the end-state criterion was set as 7 μSv/hour [92] (FIG. 56). The indicated above end-state criteria for cooling pond decommissioning should be interpreted as an averaged data for 100 m x 100 m sized plot centered around the sampling point. The gamma dose rate measurements have to be carried out at 1 m height above soil. The control levels for radioactive aerosols in the air for cooling pond decommissioning are set same as levels for the Chernobyl Exclusion zone (TABLE 29).

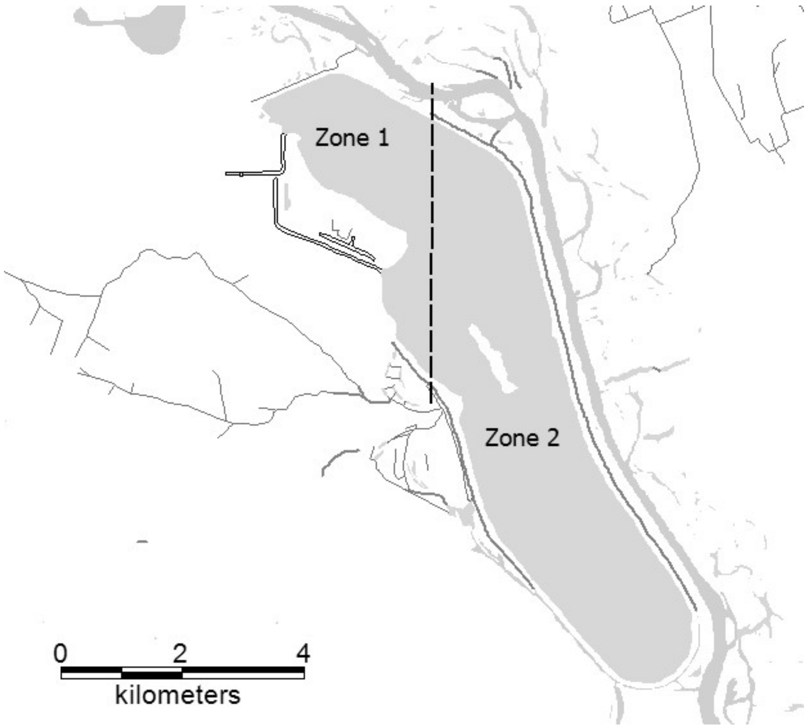


FIG. 56. Subdivision of the cooling pond area into "Northern sector" (Zone 1) and "Southern sector" (Zone 2) with respect to the radiological end-state criteria.

5.3. GENERAL SEQUENCE AND TIMING OF PLANNED DECOMMISSIONING AND REMEDIATION ACTIVITIES FOR THE COOLING POND

The feasibility study [8] has developed the following general planning for the sequence of the decommissioning, monitoring and remediation activities (if needed) of the cooling pond (TABLE 30).

TABLE 30. STAGES AND TIME FRAMES OF THE DECOMMISSIONING OF THE COOLING POND OF CHNPP (*based on data* [8])

No.	Stages	Contents of phase
1	Preparatory stage	Creating preconditions and design project documentation for the decommissioning of the cooling pond
1.1	Preparatory stage (Phase 1)	Collection and summarizing data about the cooling pond, and developing the concept for the cooling pond decommissioning (incorporating data and results from previous national and international characterization and pre-design research projects). *This phase was mainly completed in 2006 by preparing data collection report [7]*
1.2	Preparatory stage (Phase 2)	Development and approval of the Technical and Economic Feasibility study and EIA report for cooling pond decommissioning. Development of Radiation and Ecological Compliance Monitoring Programme (RECMP). Development and realization of the project design for alternative technical water supply of the ChNPP (using the existing inflow and outflow channels of the cooling pond; see section 2.1.7). Providing working condition and maintenance of the pumping equipment of the BNS-3 pumping station and of the dam of the cooling pond. *This phase was completed in 2013 by preparing and approving with the regulatory authorities of the feasibility report [8] .*
2	Phase of cooling decommissioning (drainage)	
2.1	First phase of water level lowering by 2 m (2 years)	Starting of water level lowering in the cooling pond (provisional starting date – spring 2014). The water level should be lowered during first year by 1 m during spring-summer period (split into two intervals of 0.5 m). Then the water level should be kept constant during the autumn-winter period. The same water level lowering cycle should be continued during the second year.

No.	Stages	Contents of phase
		In between water lowering periods, monitoring programme should be carried out (see section 5.4). In case of not compliance with the end-state criteria, corrective actions may be realized on drained territories (see section 5.5). At the end of cycle of water lowering, hydrological and radiological forecasts for cooling pond drainage should be updated and revised using observation data and experience gained during this phase. During this cycle, the BNS-3 pumping station should be kept in working condition.
2.2	Second phase of water level lowering from 2 m to ~ 4–5 m compared to initial water level (3 years)	During this phase, the water level lowering can proceed under influence of natural factors (seepage losses, evaporation). However, lowering of water level may be suspended in case of unforeseen unfavorable radiological or ecological conditions. Monitoring programme shall be continued (see section 5.4). During this period, new hydrological observation stations and monitoring wells shall be installed, that will be adapted to the new surface water and groundwater level conditions. In case of not compliance with the end-state criteria, corrective actions may be realized on drained territories (see section 5.5). During this cycle the BNS-3 pumping station should be kept in working condition.
2.3	Third phase of water level lowering from ~ 4–5 m to ~ 7 m compared to initial water level (~2–3 years)	During this phase, the water level lowering can proceed under influence of natural factors (seepage losses, evaporation). During this period, the cooling pond will be split in several smaller reservoirs. Monitoring programme shall continue (see section 5.4). Individual observation points can be created at different reservoirs. In case of not compliance with the end-state criteria, corrective actions shall be realized on drained territories (see section 5.5). In case monitoring data will indicate no need of suspending natural water level decline in the pond, the BNS-3 pumping station can be dismantled.
3.	Transition period from the water level drawdown in pond to the stabilization of newly created aquatic ecosystem (from ~5–6 years to ~8–9 years from the beginning	During this period, the water levels in the residual lakes will stabilize, and will correlate with hydrological conditions in Pripyat River and with the meteorological factors. During this period, additional investigations and radiological mapping of the drained areas of the pond shall be carried out. Monitoring programme can be revised and optimized. Scientific research of various consequences of pond drawdown can be carried out.

No.	Stages	Contents of phase
	of pond drainage)	Based on above studies the corrective actions (if need) may be implemented, and institutional control programme with corresponding monitoring and surveillance programmes shall be developed. By the end of this period, a decision can be taken regarding change of administrative status of this territory (for example, it can become a reserve within the territory of the Exclusion zone). In parallel, the management of this territory can be passed to some other organization affiliated to the Administration of the Chernobyl Exclusion zone. A report will be prepared regarding correspondence of the site to the decommissioning end-state criteria and radiation safety criteria. In fact, this will mean completion of the cooling pond decommissioning.
4.	Period of the long-term institutional control	After passing of the former cooling pond area to the new site owner (see previous paragraph), this organization will carry out institutional control of this territory, including monitoring and surveillance activities, in accordance with the corresponding programmes coordinated with the regulatory authorities.

5.4. COMPLIANCE MONITORING PROGRAMME

5.4.1. Objectives of the monitoring programme

The feasibility study [8] further developed general planning for radiation and environmental monitoring programme aimed at control of safe transformation of the cooling pond in the course of it’s decommissioning, which is described below.

The monitoring programme is aimed at providing information needed for decision-making in the course of the pond decommissioning by means of ‘controlled water level drawdown’.

The monitoring programme is aimed at checking compliance of the radiation (and other) parameters of the drained pond bottom areas and residual water reservoirs with the defined end-state criteria, and providing information needed for justification and planning of remedial (corrective) actions (if needed).

The monitoring programme should also provide information to public and other stakeholders on radiation safety, environmental and ecological conditions and other aspects of interest regarding cooling pond decommissioning.

5.4.2. Contents of the monitoring programme

5.4.2.1. General principles

The monitoring programme for cooling pond decommissioning shall be based and utilize to maximum extent already existing monitoring observation point networks (e.g. groundwater monitoring wells, etc.) and monitoring schedules of the general radiation monitoring programme of the Chernobyl Exclusion zone, which is carried out by state monitoring service (Ecocenter).

The general monitoring programme of Chernobyl zone, which is carried out by Ecocenter, foresees surface water and groundwater monitoring of the cooling pond. Gamma dose rate, air radioactivity monitoring and radioactive aerosol deposition rates are measured at 4 stations, installed in the vicinity of the cooling pond.

The feasibility study [8] foresaw complementing monitoring programme of the Ecocenter by additional monitoring stations and additional observations, which are discussed below. It was pointed out that some observation networks (e.g. monitoring wells) will need to be adapted to new conditions (e.g. deeper groundwater table), which will result from water level drawdown in the pond.

5.4.2.2. Contents of monitoring programme

<u>Radioactive contamination of bottom sediments (soils) within the drained areas</u>

The primary parameter of interest is external gamma dose rate from the drained pond bottom areas. Detailed dose rate surveys of the drained areas shall be complemented by bottom sediment sampling and core analyses in specific locations (e.g. “hot spots”).

<u>Air quality monitoring</u>

Air quality monitoring data (data on radioactive aerosols) are of key importance for assessing inhalation exposure doses, and for ensuring the radiation safety of staff working in the vicinity of the cooling pond.

The existing air radiation monitoring system in the vicinity of the pond (which includes 4 observation stations in northern and eastern parts of the pond) shall be extended by at least 3 mobile air monitoring stations to provide better coverage of the drained areas in western and southern sectors of the cooling pond bottom. Radioactive aerosol deposition rates shall be measured in same locations. The observations should be carried out with the weekly sampling frequency (which is the currently practiced sampling frequency at the Ecocenter monitoring network).

Standard meteorological observations shall be carried out in parallel, allowing interpretation of air quality monitoring data, and forecasting of radioactive aerosol dispersion in the atmosphere.

<u>Surface water monitoring</u>

Surface water monitoring should include radionuclide activity concentrations in groundwater (^{137}Cs, ^{90}Sr) with the sampling frequency one time per quarter. In parallel basic chemical parameters of surface water shall be determined (pH, Eh, major ions, dissolved oxygen, temperature).

Once the cooling pond will be split into several water bodies, observations should cover main individual water reservoirs.

<u>Groundwater monitoring</u>

The groundwater-monitoring programme shall continue the existing monitoring programme of the cooling pond carried out by Ecocenter. The existing monitoring well profiles between the cooling pond and Pripyat River shall be extended to follow the retreating shoreline of the cooling pond. Additional monitoring wells should be installed in order to provide data on groundwater contamination within the areas of drained bottom sediments. In such areas high sediment pore water activity concentrations are potentially expected within the former ‘stagnant’ groundwater aquifer zones below the bottom of the pond. Additional monitoring wells should be installed to the confined aquifer in Eocene deposits, in order to assess changes in conditions of water exchange between the unconfined aquifer in Quaternary deposits and confined aquifer due to water level drawdown in the pond.

Similar to surface water monitoring, the groundwater-monitoring programme should include radionuclide activity concentrations in groundwater (^{137}Cs, ^{90}Sr) and basic chemical parameters with the sampling frequency one time per quarter.

Hydro-biological monitoring

The hydro-biological monitoring is aimed at providing information on sanitary-ecological conditions and parameters of the cooling pond in order to avoid (by means of controlling water level drawdown rate) eutrophication and deterioration of the water quality in the newly formed water bodies, which may potentially lead to negative consequences such massive dying out of fish and other aquatic species.

The IHB scientists have developed a list of hydro-chemical and hydro-biological parameters with the recommended ranges of values to monitor “ecological conditions” in the pond. The list of these parameters is provided in Appendix III. The sampling should be carried out with the seasonal frequency.

Vegetation succession monitoring

Important aspect of safe cooling pond decommissioning is forming of dense enough vegetation cover within the drained area of the cooling pond. Such vegetation cover lowers risks of atmospheric resuspension of dried up bottom sediments and of surficial erosion process.

Therefore, the monitoring programme foresees regular surveys of vegetation cover within the drained pond areas. The results of survey shall serve better predictions of biological succession of drained territories, and also planning remedial measures (if needed). The surveys should be carried out with the yearly frequency (e.g. in the beginning of vegetation season).

5.4.3. Radioecological research opportunities

The cooling pond decommissioning analyses [7, 8] have pointed out that the decommissioning the cooling pond by means of (controlled) water level drawdown offers interesting and unique radioecological research opportunities.

Some radioecological research directions of interest include:

- Study of process of physical and bio-geo-chemical transformation of nuclear fuel particles and radionuclide speciation in the exposed bottom sediments;
- Study of process governing dynamics of hydro-chemical parameters and related radionuclide dynamics in the water and/or aquatic organisms of residual reservoirs;

- Various aquatic ecosystem transformation process in the course of water level drawdown in the pond;
- Developing and testing technologies of remediation of radioactively contaminated bottom sediments; etc.

Updated and extended monitoring data set from the cooling pond can be used in various radiecological model inter-comparison exercises. For example, the cooling pond data set was used previously in 1991–1996 in the IAEA BIOMOVS-II project testing models describing ^{137}Cs transport and fate in 'water – sediment' system, accumulation in biota and resulting doses to biological species and humans in aquatic ecosystems [97].

5.5. REMEDIAL APPROACHES FOR CONTAMINATED BOTTOM SEDIMENTS

5.5.1. Comparative analyses of remedial options for contaminated bottom sediments

Potential technological options for remediation of radioactively contaminated bottom sediments of the cooling pond were analyzed previously in several reports [1, 2, 4, 5].

The main technological options for radioactively contaminated bottom sediments (following the drainage of the pond) included:

- "Do nothing" option (or "natural attenuation", i.e. naturally occurring overgrowth of drained areas by vegetation);
- Removal (dredging, excavation) of radioactively contaminated bottom sediments to the external low-level radioactive waste disposal site;
- Capping of contaminated bottom sediments with clean soil layer;
- In-situ immobilization of the exposed sediments with chemical agents (e.g. dust suppressants);
- Transfer (washing-out) of the contaminated sediment into the remaining pond using high pressure water spraying, bulldozing or dredging;
- Application of phyto-stabilization methods;
- "Partial (or selective) remediation", i.e. remediation of the most contaminated sediment "hot spots" using one of the listed above methods.

Analyses carried out in [5] suggested that since the access for the staff and population to the drained areas of the pond will be generally restricted, and off-site risks caused by bottom sediment resuspension are low, the measures aimed at the large-scale decontamination of the drained parts of the cooling pond bottom are not justified.

Therefore the 'no action' option was identified as a preferred option, unless future studies and/or remediation experience show unacceptable risks due to resuspension of bottom sediments. In this last case, 'partial remediation' of some specific higher contaminated areas of the cooling pond bottom may be warranted (with the estimated integral area of < 1 km^2) [5].

The recent feasibility study of the pond decommissioning [8] has evaluated the most simple and technologically feasible options for remediation of contaminated bottom sediments:

- Deep ploughing of contaminated areas, which allows covering of the contaminated top sediment layer by cleaner soil from the depth of ploughed sediment profile.

- Removal (excavation) of contaminated bottom sediments and their disposal in the near-surface radioactive waste disposal site (RWDS) “Buryakovka” in Chernobyl zone (14 km distance from the pond);

- Capping of the contaminated bottom sediment areas with sand by means of hydraulic infill method using sand from Pripyat River channel (or from local quarry established within the cooling pond pond)

- Capping of the contaminated areas with soil screen using mechanical excavation (using the clean sand from local quarry at ChNPP site).

The cost analyses have shown that:

1. Disposal of contaminated bottom sediment (soil) material at RWDS “Buryakovka” is the most expensive method, which will limit large-scale application of this method. This method can be applied only to higher activity sources, which could have been dumped potentially to the outflow channel of the cooling pond in the course of the accident. (Provided such sources could be found in the course of cooling pond decommissioning).

2. A cheap method is deep ploughing of bottom sediments with addition of fertilizers, and seeds of perennial herbs. This method is applicable in case thickness of the contaminated bottom sediment layer does not exceed the depth of ploughing.

3. In case ploughing method is inapplicable, the following methods can be used (based on cost considerations):

- In case the area of the contaminated “hot spot” does not exceed 0.5 ha the contaminated area shall be mechanically covered by soil screen from the existing quarry;

- In case the area of the contaminated “hot spot” does exceed 0.5 ha, using of hydraulic infill method to cover the contaminated area will be economically justified. The sand for the soil cover from can be taken the bed of the cooling pond or (if not feasible) from the Pripyat River.

Preliminary analyses of [8] have shown that there is no need for large-scale bottom sediment remedial actions except for, possibly, specific hot spots situated in the northern sector of the pond (PK-5) and/or near the mouth of the outflow channel (PK-215).

5.5.2. Phyto-stabilization of drained pond bottom areas

It is expected that part of drained bottom of the cooling pond will be occupied by ‘transition’ wetland landscapes, situated between the permanently dry slopes and residual water reservoirs (see section 4.2.4; FIG. 44).

Such ‘transition’ wetlands areas can potentially dry up in summer drought periods, and refill with water during the wet seasons. In order to prevent drying up of such zones, and forming of potential sources of resuspension of radioactive aerosols from the dried up bottom sediments, phytoremediation technologies can be employed. In particular, willow plantations can be used to stabilize the drained pond bottom.

The potential of willow plantation to stabilize the contaminated soils in Chernobyl zone and to reduce risks of resuspension of radionuclides was tested within the PHYTOR project [3, 98].

The tested technique involved planting of woven mats made of willow cuttings on the surface of a partly drained small reservoir and on the transitional forms of micro-relief in the floodplain of Pripyat River. Planting of willow cuttings demonstrated positive effects following the first growing season, as it favored retaining of moisture in soil, and stabilized soils against wind erosion. By 2013, a stable vegetation cover of willow bushes is observed within the test areas.

In practice, application of the described above technology at large areas can be limited by cost considerations, and by the need to add fertilizers to the sandy bottom areas with low content of organic matter [8]. The cost of application of this method constituted approximately 6 000 USD / hectare (in prices of 2001).

5.5.3. General conclusions on the remedial actions for contaminated bottom sediments

On a whole, analyses carried out in [8] have shown that most likely (considering the available data and results of analyses of scenarios of the cooling pond drainage), large scale remedial measures for the exposed bottom sediments will not be justified.

However, at specific sites where the staff of ChNPP may need to carry out works, in particular in the northern sector of the pond (PK-5), and near the mouth of the outflow channel (PK-215), under certain conditions remedial works may be implemented, aimed at lowering of the gamma external dose rate values and mitigation of radioactive aerosol resuspension. The preferred (cheapest, simple) technology of remedial measures is deep ploughing of bottom sediments with addition of mineral fertilizers, organic substrate (turf) and addition of seeds of perennial herbs.

The decision regarding the necessity of remediation of bottom sediments shall be taken based on result of the repeated gamma-dose rate measurements and investigation of the contamination levels of the exposed bottom sediments in the drained areas of the pond in the course of the water level drawdown. The justification and “cost – benefit” analysis of such measures should be carried out in each specific case.

6. MODELLING PREDICTIONS VS. ACTUAL CONSEQUENCES OF THE COOLING POND LEVEL DRAW-DOWN IN 2014–2017

6.1. OVERVIEW OF COOLING POND DRAWDOWN IN 2014–2017

The cooling pond decommissioning started in May 2014, when the pond pumping station was switched off, and water level in the pond start to decline due to seepage and evaporation losses.

Due to technological reasons, the water level drawdown in the pond during first 3 years proceeded in a continuous (rather than step-wise or "controlled") mode. During summer – autumn period of 2014 the water level in Pripyat River was at historically low levels of about 101–102 m a.s.l. Such low levels in Pripyat River did not allow operation of the cooling pond pumping station, as the water level in the receiving chamber was too low. However, as the prescribed radiological and ecological parameters have not been violated in the process of pond drainage during the first and subsequent years, therefore there was no urgent need to put the pumping station into operation in order to suspend water level drawdown for corrective actions.

During the period from May 2014 to mid-summer 2016 the water level in the pond has dropped by about ≈4 m. Once the water level in the pond reached the elevation of ~ 106.5 m a.s.l. in August 2016, the pond has split into three separate water bodies with different water levels (FIG. 57). The water reservoir in the southern part of the pond is separated from the rest of the pond by the former dam of the first stage of the cooling pond, which have emerged to the surface in the course of pond drainage. The other two reservoirs situated in the northern part of the pond are separated from each other by the current guiding dike and by the former dam of the first stage of the cooling pond. By mid-summer 2017 the drained area of the cooling pond bottom has reached ≈40% of the initial area of the pond surface (FIG. 58).

Monitoring programme carried out in the course of the pond water level drawdown generally followed the initial plan described in section 5.4.2. Collected monitoring data allow comparison of modeling predictions and actual dynamics of hydrological, radioecological and ecological parameters of the cooling pond in the course of water level drawdown. Such comparisons are presented in the next sub-section of this chapter.

The comparisons are carried out with respect to the following parameters:

- Water level drawdown rates (surface water, groundwater);
- Bathymetry of the pond;
- Radioactive aerosol resuspension from drained pond bottom areas;
- Dissolution rates of fuel particles in the exposed bottom sediments;
- Dose rates from the exposed bottom sediments;
- Radionuclide concentrations in the water of residual reservoirs;
- Dynamics of overgrowth of the pond bottom by vegetation, and
- Consequences to the aquatic ecosystem of the pond.

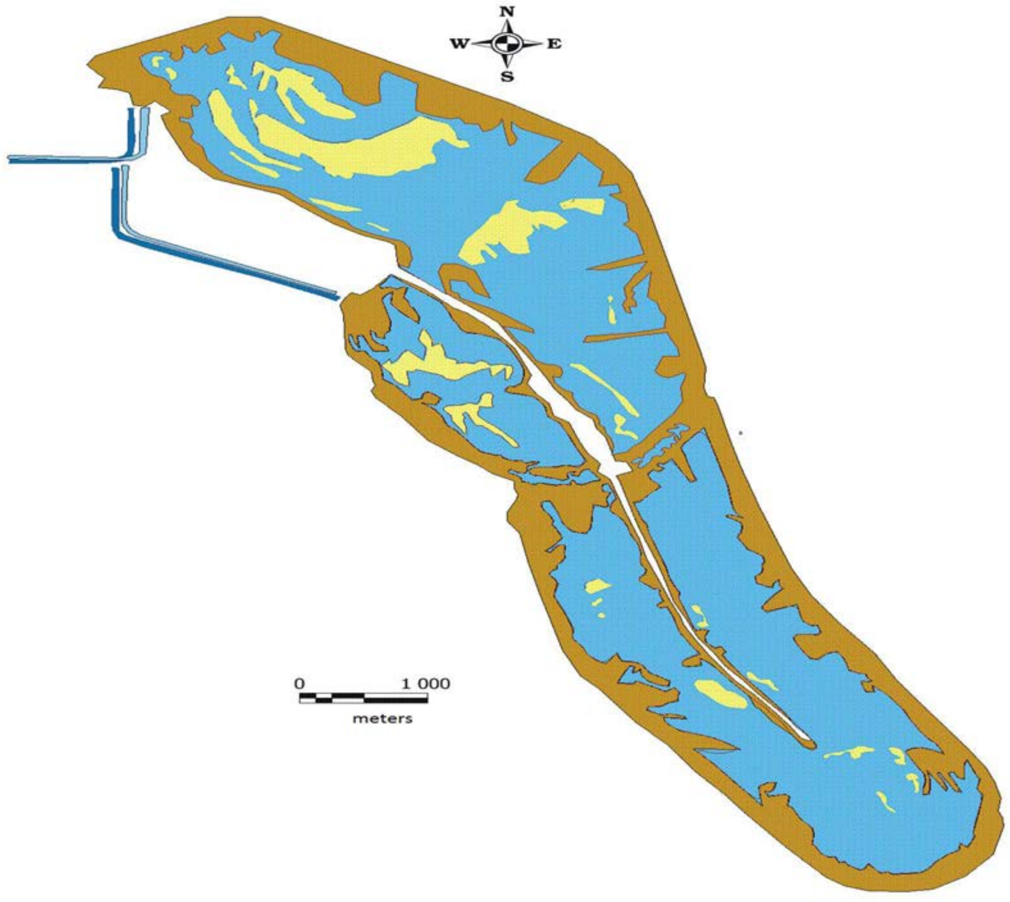


FIG. 57. Scheme of exposed bottom areas of the pond in August 2016 based on analyses of the satellite photo (Google Earth Vision). (Exposed beach areas are shown in brown color; exposed inner shallow zones and 'islands' are shown in yellow color).

FIG. 58. View on the drained bottom of the cooling pond from the former pumping station (from the northeast corner of the pond, October 2017) (reproduced courtesy of D.Bugai, IGS).

6.2. COMPARISON OF MODELLING PREDICTIONS AND ACTUAL CONSEQUENCES OF POND DRAINAGE

6.2.1. Water level drawdown rate

6.2.1.1. Pond surface water level regime

Dynamics of water level drawdown in the pond along with the modeling predictions is shown in FIG. 59. (The modeling methodology is described in section 4.2).

During first year water level in the pond decreased with the rate close to 'normal' climatic modeling scenario. In 2015 – 2016 the rate of water level drawdown started showing sensitivity to climatic conditions being higher in the warm seasons and being lower during the cold seasons. The actual water level in the pond during this period was bounded by modeling graphs corresponding to 'normal' and 'dry' scenarios (FIG. 59).

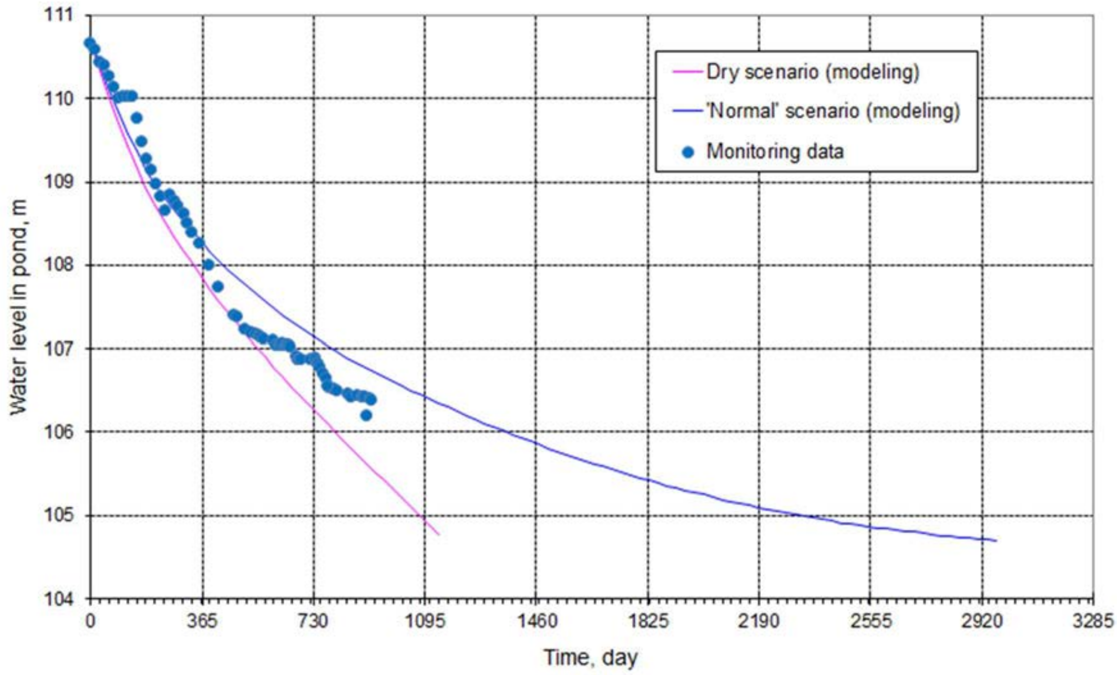


FIG. 59. Water level drawdown rate in the pond: comparison of modeling predictions and monitoring data.

During 2015 the yearly precipitation was 608 mm (close to multiannual average), while 2016 was a "dry" year with the yearly precipitation of 403 mm (based on Chernobyl weather station data; see Appendix II for data on average multi-annual meteorological parameters).

On a whole, a reasonable agreement of the actual pond drainage dynamics with *a priori* modeling assessment described in section 4.2 was observed.

In the second half of 2016 and in 2017 the surface water levels in the isolated reservoirs located in northern and southern sections of the cooling pond continued to decrease gradually approaching the predicted end-state levels for the "normal" climatic scenario (i.e. 105.5 m a.s.l. in northwest part of the pond bottom, and 104.7 m in the southern part of the former pond; see section 4.2.4.) (FIG. 60).

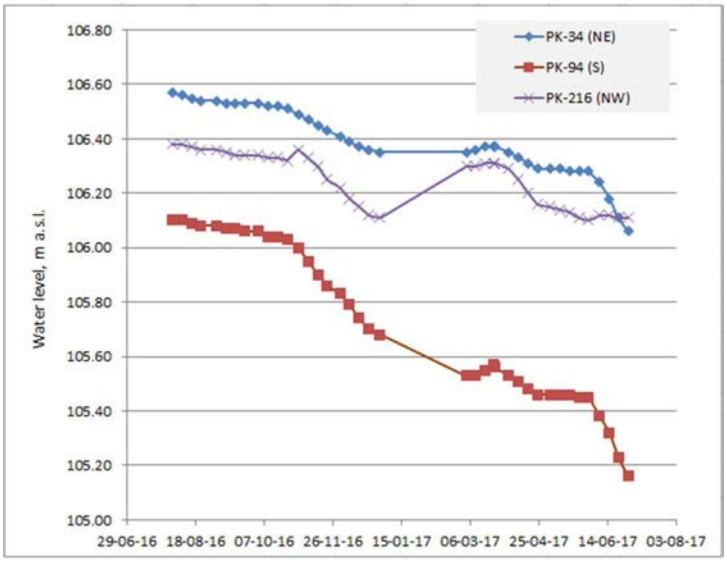


FIG. 60. Water level dynamics in the individual reservoirs in northeast, northwest and southern part of the cooling pond during 2016 – 2017 (data of ChNPP).

During 2016–2017, the water levels in northern part of the pond were by 0.5 m – 1 m higher than in the southern part of the pond. This is in qualitative and quantitative agreement with the modeling predictions (see section 4.2.4).

6.2.1.2. Ground water level regime

As expected, drainage of the cooling pond has caused groundwater level drawdown in its vicinity including the Industrial Site of ChNPP.

Data on groundwater level drawdown in selected monitoring wells situated at ChNPP industrial site in 2013–2017 are in listed TABLE 31 and are shown in FIG. 61. The depth to groundwater table increased on an average about 1.8–2 m.

An example well hydrograph in well no.12-2A situated near Sarcophagus (~1500 m west from the pond) is shown in FIG. 62. Here the groundwater level has decreased in 2014–2017 by ~ 1.5 m.

The groundwater level near RWDS “3rd stage”, which is situated in the immediate vicinity of the cooling pond (see section 3.7.2) has decreased in 2014 –2016 by 3.5 m (FIG. 63). In the following period in majority of monitoring wells groundwater table dropped below the screened interval, so that further observations were not possible. The monitoring system for this site requires upgrading by drilling monitoring wells adapted to the new hydrogeological conditions.

These discussed above changes in groundwater levels at ChNPP Industrial Site and in vicinity of the cooling pond generally agree with the *apriori* groundwater modeling predictions (see section 4.2.4).

TABLE 31. WATER LEVEL DECLINE IN SELECTED PIEZOMETERS AT INDUSTRIAL SITE (UNITS 1 AND 2) OF CHNPP IN 2013–2017 (*data of* ChNPP)

Piezometer number	Mean level in 2013, m a.s.l.	Mean level in 2017, m a.s.l.	Difference in levels, m
P-42	110.00	108.02	1.98
P-52	110.80	108.99	1.80
P-55	110.92	109.08	1.83
P-57	109.52	107.64	1.88
P-60	109.41	107.30	2.12
P-66	110.43	108.68	1.74

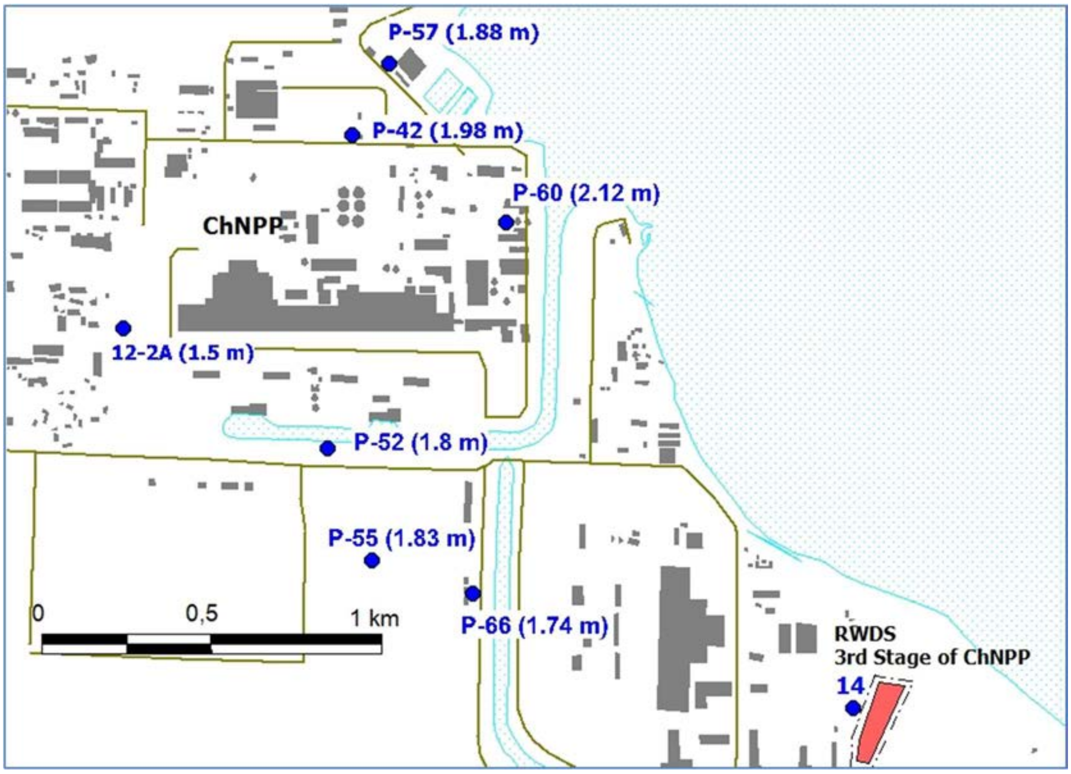


FIG. 61. Scheme showing location of selected piezometers at ChNPP Industrial Site and mean values of groundwater level drawdown in 2013– 2017 (data of ChNPP, ISP NPP).

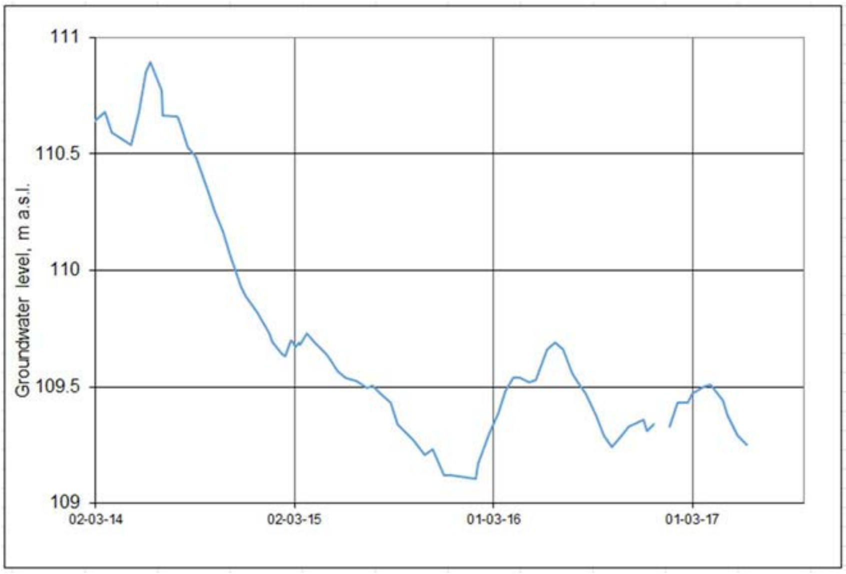


FIG. 62. Groundwater level regime in well no.12-2A located near the west wall of Sarcophagus (data of the ISP NPP).

FIG. 63. Groundwater level regime in well no.14 at RWDS "3rd Stage of ChNPP" in 2013 – 2016 (data of the SSE "Ecocenter").

6.2.2. Bottom topography

Bottom topography of the cooling pond revealed in the course of water level drawdown, which can be seen on the satellite photo of the cooling pond from August 2016 (FIG. 57), shows some noticeable differences compared to the *a priori* predictions using the 3D numerical model based on bathymetry survey carried out in 2001 (described in section 2.1.5.1).

Well-defined geometries of former channels of Pripyat River, dam of the 1st stage of the cooling pond and other details of bottom relief can be clearly distinguished on the satellite photo (FIG. 57).

Some of the mentioned above details of the pond bottom topography cannot be readily distinguished with the 3D numerical pond bottom relief model based on bathymetry data (see section 2.1.5.1).

Further comparison of the satellite photo of the pond from August 2017with the superimposed bottom isoline of Z=105.5 m a.s.l. of the 3D numerical model of the pond bottom topography is presented in FIG. 64. The non-perfect correspondence of the model with the satellite data is observed mainly in the northwest corner of the pond bottom area.

The mentioned above inaccuracies in the 3D numerical model of pond bottom based on bathymetry survey of 2001 may have been caused by a number of reasons, including: the sparse measuring grid (which has not been able to capture small-scale details of bottom relief), sampling point positioning errors (e.g. in the northwest part of the pond), as well as (possibly) by inaccuracies caused by interpolation techniques used (i.e. kriging interpolation).

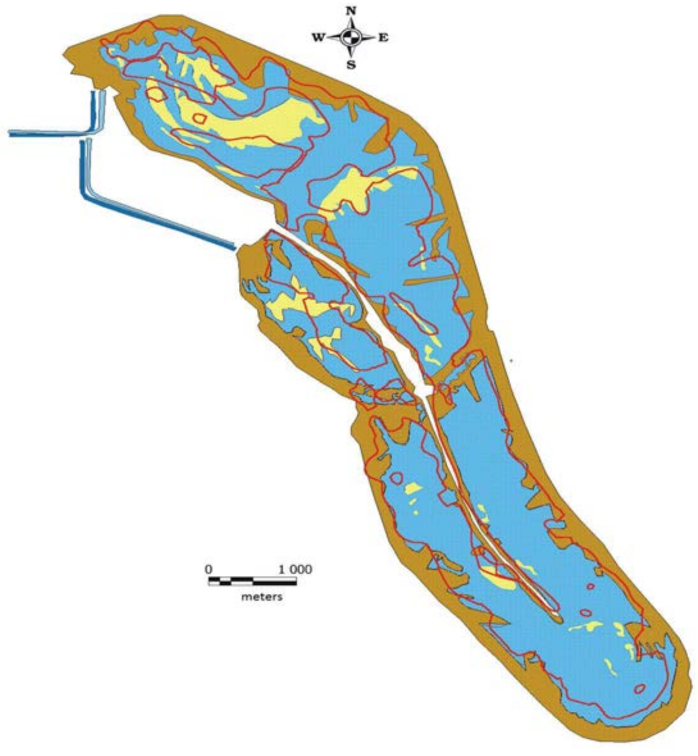


FIG. 64. Comparison of the scheme of the exposed bottom areas based on satellite photo of the pond (August 2016) with the Z=105.5 m a.s.l. isoline of the 3D numerical model of pond bottom topography.

6.2.3. Radioactive aerosol resuspension

Monitoring studies of the ChNPP [99, 100] and SSE "Ecocenter" (radiation monitoring service of Chernobyl exclusion zone) have not revealed in 2014–2017 any significant impact of the water level drawdown in the cooling pond on the radioactive aerosol activities in the air at ChNPP site and in Chernobyl town.

It should be noted that during the discussed period, there were no dust storms or grassland fires within the drained cooling pond bottom areas, which could have potentially lead to noticeable increase of resuspension of radioactivity from the pond bottom (see section 4.3).

Monitoring data of the SSE "Ecocenter" on ^{137}Cs airborne concentrations in the monitoring checkpoints in the vicinity of the cooling pond along with the modeling predictions for 'Normal scenario' of atmospheric transport of radioactive aerosols (see section 4.3) are listed in TABLE 32. On a whole, radionuclide airborne concentrations at ChNPP site in 2016–2017 were comparable to previous years. Modeling analyses indicate that increase in volumetric radionuclide activity in air for 'normal atmospheric conditions' is rather low, so that it may not be possible to reveal the influence of radionuclide resuspension from the drained pond bottom areas compared to the existing relatively high background radionuclide airborne concentrations at the monitoring points, for the reason of natural fluctuations of airborne activity and accuracy of measurements (see TABLE 32).

TABLE 32. THE MAXIMUM ^{137}CS AIRBORNE CONCENTRATIONS IN THE MONITORING CHECKPOINTS OF THE SSE "ECOCENTER" IN THE VICINITY OF THE COOLING POND OF CHNPP BEFORE AND AFTER OF WATER LEVEL DRAWDOWN IN THE COOLING POND (*based on data of the* SSE "ECOCENTER")

Monitoring station	Monitoring data of SSE "Ecocenter"			Modeling predictions
	2008–2014	2016	2017	Increase for Scenario 1 ('normal conditions')
	Annual averaged airborne concentration, Bq/m^3			
"VRP-750"	2.5×10^{-3}	3.6×10^{-3}	1.2×10^{-3}	1.3×10^{-5}
"Neftebaza"	6.1×10^{-4}	8.7×10^{-4}	3.0×10^{-4}	NA
"BNS-3"	1.7×10^{-4}	2.9×10^{-4}	1.5×10^{-4}	NA
	5-days averaged airborne concentration, Bq/m^3			
"VRP-750"	$\leq2.1\times10^{-2}$	$\leq4.4\times10^{-2}$	$\leq4.4\times10^{-3}$	1.3×10^{-5}
"Neftebaza"	$\leq4.7\times10^{-3}$	$\leq1.1\times10^{-2}$	$\leq1.3\times10^{-3}$	NA
"BNS-3"	$\leq4.5\times10^{-4}$	$\leq4.4\times10^{-3}$	$\leq5.9\times10^{-4}$	NA

Note: "VRP-750" monitoring station is situated at 1 km S from ChNPP; "Neftebaza" is situated 2 km NW from ChNPP; "BNS-3" is situated 2.6 km E from ChNPP.

It should be pointed out that there were other important factors causing generation of radioactive aerosols at ChNPP site in 2016, in particular construction works on erection of the New Safe Confinement. There was also a forest fire during 15–18 July 2016 in the most contaminated part of the ChEZ with an area of 300 hectares (territory of the so-called "Red Forest").

Relatively high values of the 5days averaged radionuclides airborne concentrations, registered in 2016, were related to the mentioned above factors, and were not related to radioactive aerosols resuspension from the drained bottom areas of the cooling bottom. Analysis shows that these elevated radioactive aerosol concentrations were registered at the respective monitoring stations in calm or light wind conditions (e.g. a wind speed of less than 1 m/s), and in cases of wind directions originating from other than cooling pond areas.

Moreover, despite the expansion of the drained bottom area of the cooling pond in 2017, maximal values of the 5 days averaged ^{137}Cs airborne concentrations were lower in 2017 than those ones in 2016 by factors of 3 to 10 (see TABLE 32).

According to the data of the radiation monitoring department of ChNPP [99, 100], ^{137}Cs and ^{90}Sr atmospheric deposition rates in November 2016–September 2017 in the immediate peripheral areas of the cooling pond were 0.2÷12 Bq/(m^2 day). These values are in agreement with the predicted deposition rates of 0.5÷5 Bq/(m^2 day) for bottom sediments contamination densities of 1000÷10000 kBq/m^2, averaged coefficient of resuspension of 5×10^{-10} m^{-1} and dry deposition rate of radioactive aerosol of 1 cm/s (see section 4.3).

Based on the monitoring data collected in 2016–2017 by radiation monitoring department of ChNPP, it was concluded that the volumetric activity of radionuclides in the surface layer of the atmosphere during the decommissioning the cooling did not cause any essential additional increase in the inhalation doses for staff members at the ChNPP industrial site and in Chernobyl town [99, 100].

6.2.3. Dissolution rates of fuel particles in bottom sediments

Model experiment was carried out in 2012–2016 to estimate the dynamics of fuel particle dissolution and radionuclides speciation in drained (dewatered) bottom sediments of the cooling pond [101].

About 150 L of bottom sediments were collected in the northwest part of the cooling pond from several sampling point in the depth of interval of 4 to 7 m. The collected bottom sediments were placed inside the 1 m x 1 m 'cassette' without bottom installed at the beach of the cooling pond (FIG. 65).

In the course of the experiment, samples of exposed bottom sediments were periodically collected from the inside of the cassette, and analyses of radionuclide speciation were carried out by the method of sequential extractions (TABLE 33). The results of this experiment are presented in FIG. 66, and are briefly summarized below.

In the beginning of the experiment, the main part of radionuclides (> 98 %) were present in bottom sediments in non-exchangeable forms, while 70 % of ^{90}Sr and more than 80 % of ^{241}Am and plutonium isotopes were presumably associated with fuel particles (FIG. 66).

In the course of exposure in natural conditions during 4 years, the increase of water-soluble forms of ^{90}Sr was observed (by a factor of up to ~5). However, the resulting cumulative increase of the ^{90}Sr content in water-soluble form was relatively small (up to 0.6 % of total content). The content of water-soluble forms of other radionuclides did not change significantly over time, and remained rather low during the whole experiment (< 0.1 % of total content).

FIG. 65. Cassette with the exposed bottom sediments of the cooling pond (October 2012) (reproduced courtesy of V.Protsak, UIAR).

The amount of exchangeable ^{90}Sr increased in the course of the experiment from ~ 1 % to ~ 10 % of the total content. The content of exchangeable forms of other radionuclides did not change significantly, and was less than 2 % of the total content.

TABLE 33. SEQUENTIAL LEACHING PROCEDURE APPLIED TO THE BOTTOM SEDIMENTS OF THE COOLING POND

No.	Leaching agent and conditions	Chemical forms of radionuclides
I	Distilled water, 24 hours, t=20 C	Water soluble
II	1 M CH_3COONH_4 (NH_4Ac); 24 hours, t=20 C	Exchangeable
III	1 M HCl; 24 hours, t=20 C	Acid-soluble
IV	0.2 M $(NH_4)_2C_2O_4$ + 0.1 M $H_2C_2O_4$ (Tamm solution); pH 3,2; 2 hours, t=20 C	Associated with amorphous oxides and hydroxides of Fe and Al in the form of mineral-organic complexes

V	8 M HNO_3; 24 hours, t=20 C	Poorly soluble and associated with fuel particles (U_xO_y + UO_2 matrix)
VI	Heating at 550 °C during 6 hours, following by leaching by acid mixture of 8 M HNO_3 + 10 M HCl, 2 hours, 95° C	Associated to organic components of bottom sediments and fuel particles (UO_2 matrix)
VII	Acid mixture 8 M HNO_3 + 4 M HF, 2 hours, 95° C	Strongly fixed by mineral components of bottom sediments and associated with fuel particles with zirconium containing matrix ($U_xZ_yO_z$)
VIII		Insoluble residue

On a whole, relatively small changes of the content of mobile forms (water-soluble + exchangeable) of radionuclides in the dewatered and exposed in the natural conditions bottom sediments of the cooling pond were observed on the experimental time scale of 4 years. The observed buildup of mobile forms of ^{90}Sr can be interpreted as a result of relatively 'slow' dissolution process of fuel particles with the matrix of UO_2 (see section 3.3.2 of this report for discussion of different types of fuel particles in Chernobyl fallout).

The bottom sediments at the experimental site were characterized during the whole duration of the experiment by the slightly alkaline pH values (e.g. pH ~7.7; FIG. 67). Such geochemical conditions favored low dissolution rates of fuel particles. This observation does not support the hypothesis that the drainage of the pond can lead to the increase of acidity of bottom sediments promoting dissolution of fuel particles [34].

The observed increase of water soluble and exchangeable forms of ^{90}Sr by ~10 % during 4 years corresponds to the value of the effective half-dissolution period for fuel particles in the exposed bottom sediments of 25 years. This last value is two times larger than the previously estimated one (FIG. 50 in section 4.5).

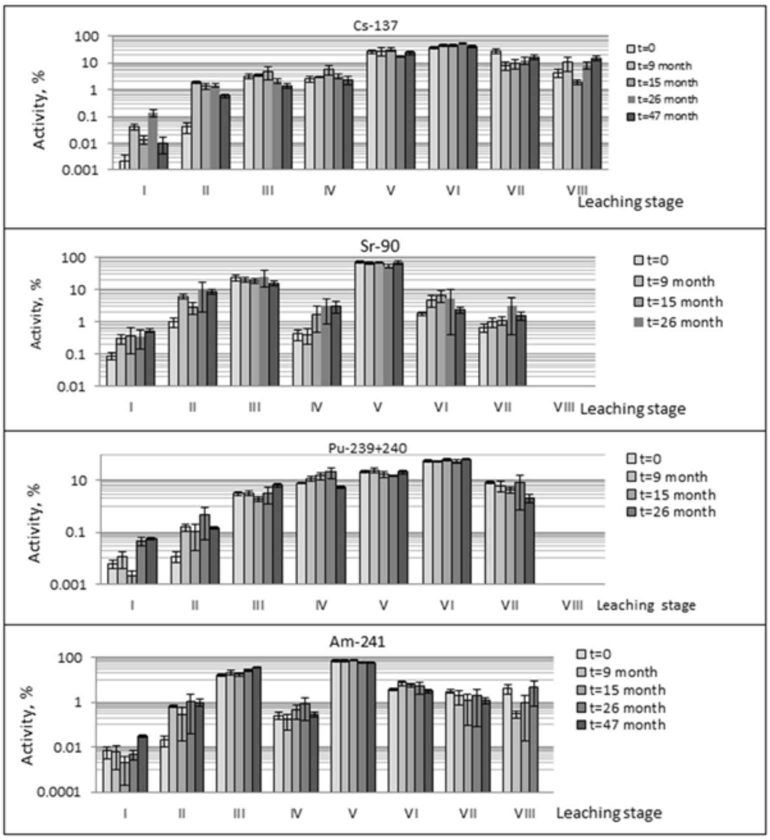


FIG. 66. The dynamics of chemical forms of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am in the exposed bottom sediments of the cooling pond determined using the sequential leaching procedure described in TABLE 33 (based on data [101]).

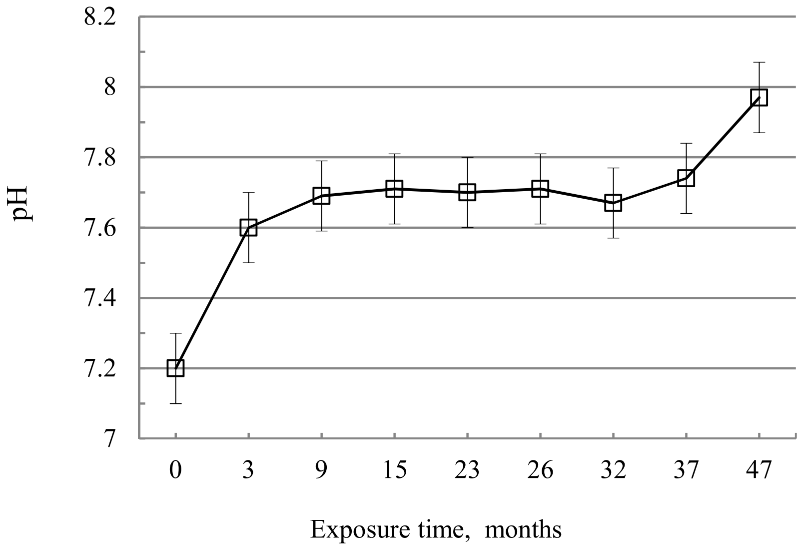


FIG. 67. Dynamics of pH of the exposed bottom sediments of the cooling pond (based on data [101]).

Radiographic studies confirmed presence of the Chernobyl fuel particles in the bottom sediments of the Cooling pond (FIG. 68). It was established that the majority of fuel particles have a size of 3 μm and less, however their contribution to the total activity of bottom sediments is several percent only. The main part of the activity in bottom sediments is contributed by fuel particles of about ~20 μm size. Therefore, it can be concluded that the future time evolution of mobile forms of radionuclide will be determined by the processes of destruction and leaching of radionuclides from such relatively large (several tenths of μm) fuel particles.

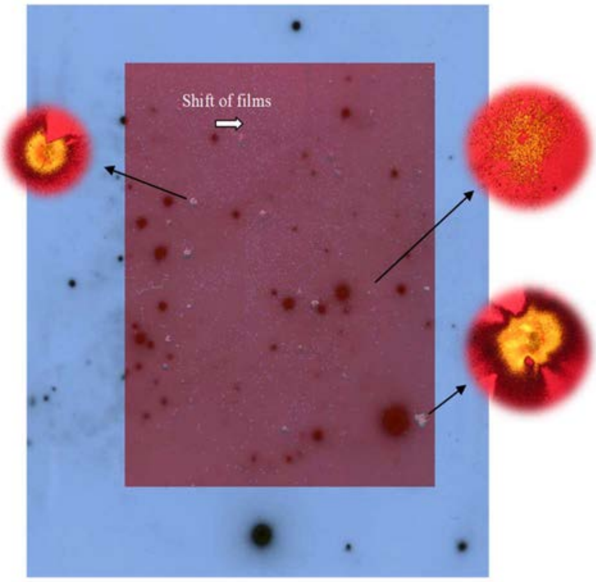


FIG. 68. The X-ray film and the LR 115 film for α-track radiography after joint exposure on a sample of bottom sediments of the cooling pond showing tracks from fuel particles (reproduced courtesy of V.Protsak, UIAR).

To summarize, the results of the described above experiment [101] suggest that mobility of radionuclides in the exposed bottom sediments of the cooling pond may be noticeably lower than predicted earlier (see section 4.5).

Significant part of the radionuclide activities cannot be extracted from the solid phase of the bottom sediments even when applying the 'extremely aggressive' laboratory leaching conditions. This may be indicative that part of ^{90}Sr, $^{238,239,240}Pu$, ^{241}Am and ^{137}Cs are associated with the very chemically stable fuel particles. It is expected that this part of radionuclides shall not be mobilized in the natural conditions at least for several decades. One more reason for relatively low dissolution rate of fuel particles in bottom sediments is relatively stable in time geochemical conditions characterized by slightly alkaline pH values. The potentially mobile fraction of radionuclides (which can be mobilized during the next 5–10 years) is estimated at less than 30 % of the total content of radionuclides in bottom sediments. It should be pointed out that only radionuclides, which are presented in mobile forms, can be potentially involved in hydrologic migration processes and uptake by vegetation.

6.2.4. Dose rates from exposed bottom sediments

Based on *a priori* estimation, the highest external gamma dose rates from the exposed bottom sediments of the cooling pond contaminated with ^{137}Cs were expected in the northwest part of the drained pond bottom and in the area close to the mouth of the outflow channel of the cooling pond (see section 4.4, FIG. 49). In order to assess the reliability of the performed predictions, the UIAR research team (supervised by V.Kashparov) has carried out in 2017 field measurements of the external gamma dose rates (EDR) at the drained bottom of the cooling pond in the respective locations (FIG. 69).

The measuring Site no.1 has been chosen within the area, where the maximal external gamma dose rates were observed in the northwest part of the drained pond bottom in 2017. It is situated 100 m southwest of the area, where the maximum levels of the contamination density with ^{137}Cs of the drained bottom sediments have been predicted (FIG. 69).

Results of the gamma dose rate survey at Site no.1 are shown in FIG. 70. As predicted, the maximum EDR values in this area were higher than the reference end-state remediation criterion of 14 µSv/hour established for the northern part of the pond (see section 5.2.2). At the same time, the maximal measured values of the external gamma dose rate of ~ 50 $\mu Sv\ h^{-1}$ are about two times higher than the *a priori* estimates (see section 4.4).

The discrepancy of about the factor of 2 between the *a priori* predictions and *a posteriori* experimental data can be explained by several factors. It should be noted that it turned out that the ^{137}Cs is relatively evenly distributed within the 20 cm thick layer of drained bottom sediments at Site no.1 (FIG. 71), while the *a priori* assessment assumed that the ^{137}Cs is concentrated in the 5 cm top layer only.

One other possible reason is that the map of ^{137}Cs distribution in bottom sediments used to calculate the external dose rate was based on a relatively sparse bottom sediment sampling grid, so that some local small-scale "hot spots" may have been missed.

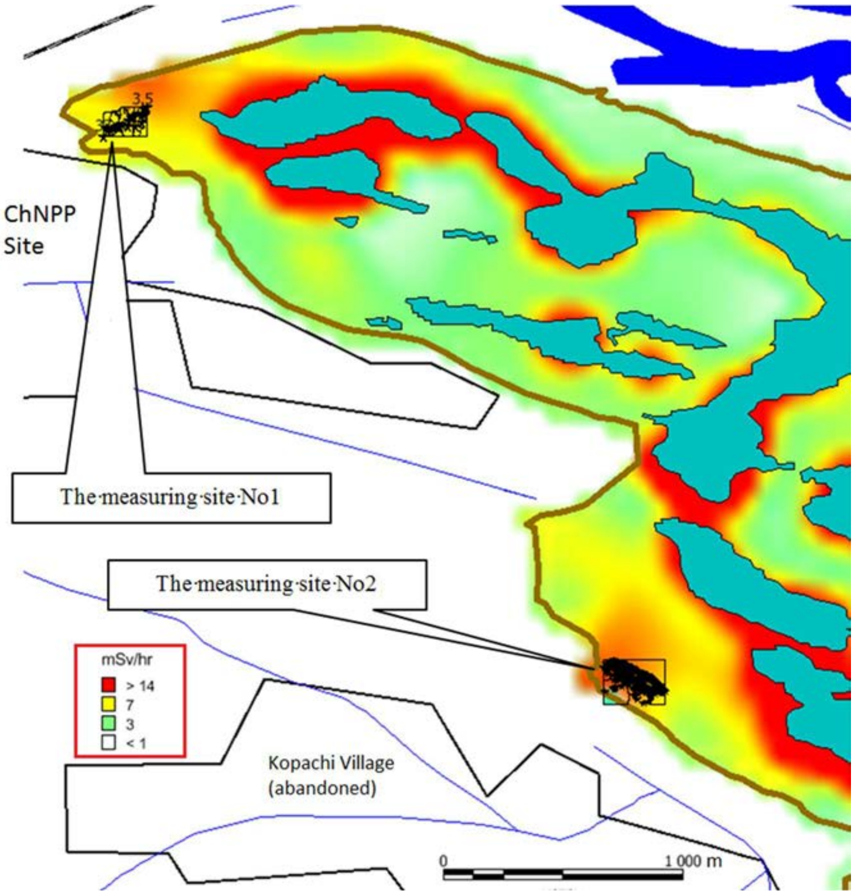


FIG. 69. Location of field measuring sites for checking a priori external dose rate estimates from the exposed bottom sediments of the cooling pond. The estimated distribution of external gamma dose rate at 1 m height above bottom sediments is shown in the background (for the model assuming that ^{137}Cs activity is evenly distributed in the top 5 cm layer).

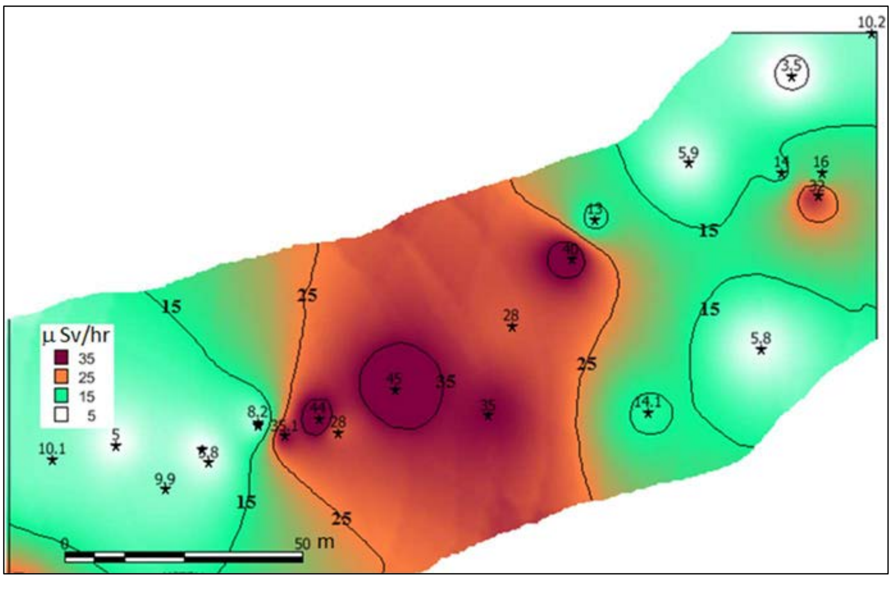


FIG. 70. Distribution of external gamma dose rate on Site no. 1 in 2017 (based on data of the UIAR).

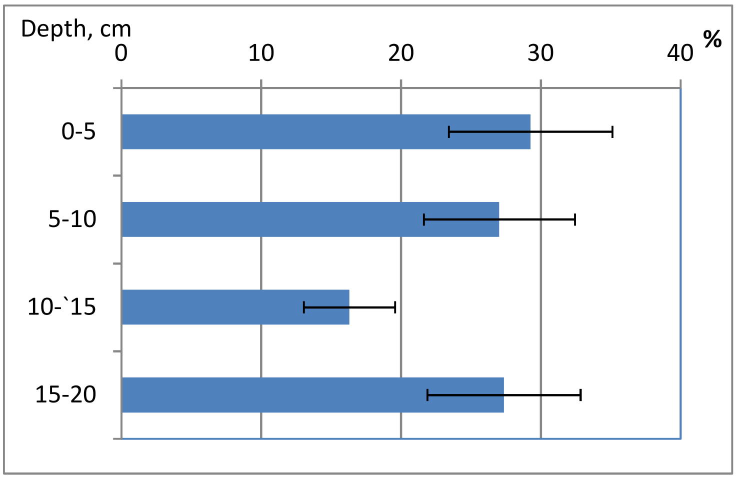


FIG. 71. Typical vertical distribution of ^{137}Cs (in % of total inventory within the profile) in the bottom sediments at Site no.1 in 2017 (based on data of the UIAR).

In addition, the redistribution of radionuclide activities in the drained bottom areas in the process of water level drawdown in 2014 – 2017 (e.g. by wave action) cannot be excluded. Maximal values of the EDR were observed at the sites of silty bottom sediments of dark color, which likely had a very good ability to fix ^{137}Cs from solution and may be potentially related to fine sediments 'traps' formed at the retreating shoreline in the course of the water level drawdown.

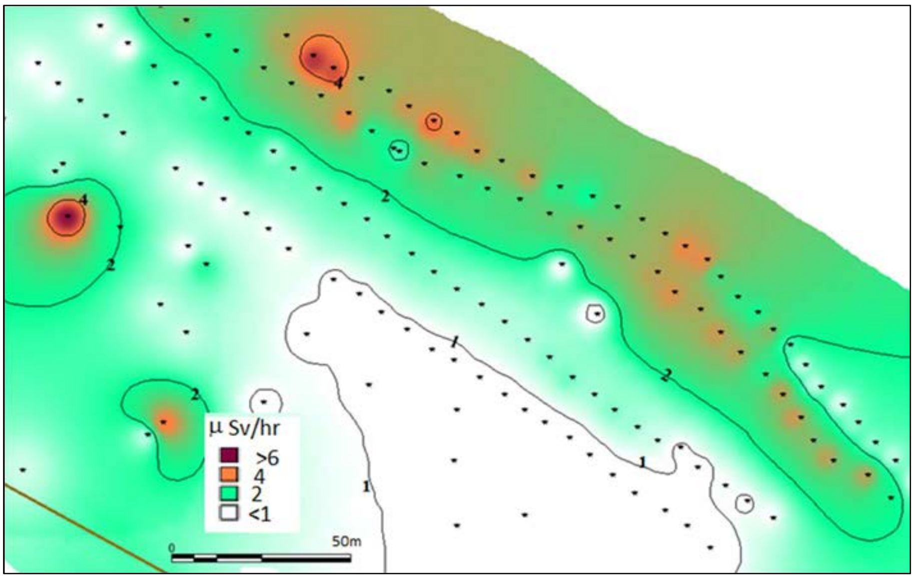


FIG. 72. Distribution of external gamma dose rate on Site no. 2 in 2017 (based on data of the UIAR).

The external gamma dose rate distribution in the pond bottom area adjacent to the mouth of the outflow channel (the measuring Site no. 2) is shown in FIG. 72. Here the measured EDR values are generally in good agreement with the initial estimates, and do not exceed the reference end-state criterion of 7 µSv h^{-1} for the southern sector of the cooling pond. At this site the main part of the ^{137}Cs activity was concentrated in a top 5 cm layer of sediment (FIG. 73) (which confirms to the assumptions used in *a priori* calculations).

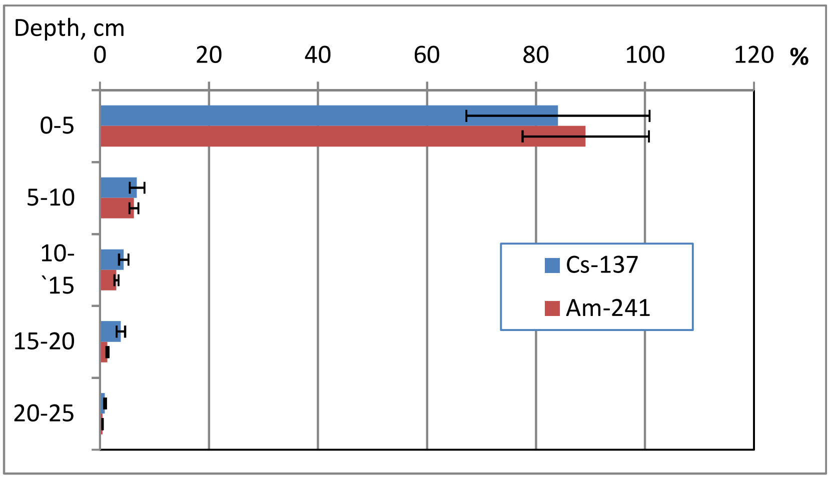


FIG. 73. Typical vertical distribution of ^{137}Cs (in % of total inventory within the profile) in the bottom sediments at Site no.2 in 2017 (based on data of the UIAR).

It should be reminded, that the end-state EDR criteria should be interpreted as an averaged data for 100 m × 100 m sized plot centered around the sampling point (see section 5.2.2). In this case, average values of the EDR likely will be significantly lower than the reported above maximal point values in local "hot spots".

The exposure dose rates were monitored by the ChNPP in several external locations around the perimeter of the cooling pond in 2008–2013 (before the water level drawdown) and after drainage of the bottom sediments of the cooling pond during November 2016 – August 2017. The results of this monitoring show that drainage of the bottom sediments had no effect on the EDR values, and did not increase the risk of additional exposure of the staff in the external areas adjacent to the cooling pond perimeter.

Thus, it can be concluded, that the measured exposure dose rate values in the drained bottom areas were generally in reasonable agreement with the *a priori* estimations (e.g. within the factor of ~2 or less).

Though the measured exposure dose rate values in the northern part of the cooling pond are relatively high, and some point measurements exceed initial modeling estimates, these measured gamma dose values still are comparable to contamination levels observed in some other locations of the ChEZ (for example, at "Red Forest" site, and at the left-bank of the floodplain of Pripyat River the gamma dose rate levels reach 100 μSv h^{-1}).

As it was mentioned above, the maximal values of the external gamma dose rate were observed in locations with silty bottom sediments of dark color. Such areas are characterized high soil fertility, caused by the lithological composition of material and by the high content of organic matter, which resulted in rapid growth and dense grass and vegetation cover at these sites. This reduces the risk of secondary resuspension of radioactive aerosols from the pond bottom with the wind.

6.2.5. Radionuclide concentrations in water of residual lakes

Surface water monitoring at ChNPP cooling pond was carried out in 2014–2017 by several organizations and institutes including ChNPP, SSE "Ecocenter", IHB and UHMI.

Based on monitoring data of all institutes radionuclide concentrations (^{137}Cs, ^{90}Sr) in water of residual reservoirs have shown tendency to increase since 2015. Such an increase can be explained by changed water balance of the cooling pond after decommissioning (i.e. stopping of pumping of relatively 'clean' water from Pripyat River, decrease of seepage losses, etc.), and by radioactivity exchange between the contaminated bottom sediments and surface water column.

Based on data of ChNPP [100], in the third quarter of 2017 an increase of ^{90}Sr activity has been observed in pond surface water up to 4.2 Bq/L in Southern sector and 8 Bq/L in the Northern sector, while ^{137}Cs activity increased throughout all reservoirs up to 4 Bq/L in Northern sector, and up to 6.5 Bq/L in the Southern sector. Similar increasing trends for ^{90}Sr activity in surface water of the residual lakes in 2017 are reported by SSE "Ecocenter". For comparison, the mean yearly ^{137}Cs and ^{90}Sr concentrations in the water of the pond were noticeably lower, and constituted 1–1.5 ±0.5 Bq/L in 2012–2013 (see section 3.3).

It should be noted, however, that ChNPP and SSE "Ecocenter" carry out surface water sampling in the shallow near-shoreline areas of lakes, and therefore sampling results can be potentially sensitive to enhanced water mixing in such areas caused by wind/wave actions etc.

The reported above measured maximum ^{90}Sr concentrations in the water of residual lakes are so far lower than the *apriori* estimated long-term maximum ^{90}Sr activity concentration in the water of residual reservoirs of 40 to 70 Bq/l (based on conservative analysis of [41]; see section 4.6.1.3).

6.2.6. Dynamics of overgrowth of pond bottom by vegetation

The vegetation cover of the drained areas within the cooling pond was formed in the course of its drainage in 2014–2017 in accordance with the soil conditions, primarily depending on lithology, fertility and moisture regime of the drained bottom sediments.

Processing of the space image of the Sentinel 2 satellite (from 11.08.2017) allowed to identify within the drained pond bottom area of 943.3 ha (that is 42 % of the initial pond surface water area) 3 types of the newly formed land with respect to vegetation cover (FIG. 74) [102]:

- Low-laying wetlands, overgrown with marsh grasses, shrubby and arboreal plants (510.7 ha, or 54 % of the drained bottom area);
- Sandy sites covered with shells, usually sparsely overgrown (240.8 ha, or 26%);
- Elevated sandy sites of the newly formed land (191.8 ha, or 20%).

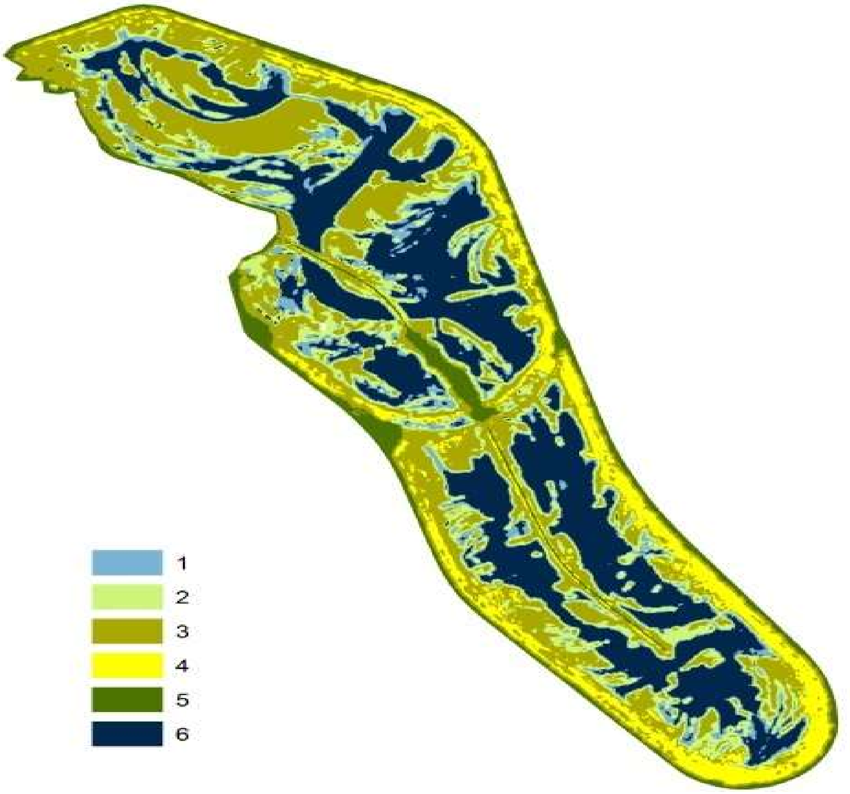


FIG. 74. Map of distribution of land areas with different sediment types and vegetation covers within the drained pond bottom as on 11.08.201: 1 –shallow water sites (not overgrown); 2 – shallow water sites, overgrown with macrophytes; 3 – wetlands; 4 –sandy sites with shells, 5 – elevated crests; 6 – deep water sites (based on data [102]).

Fertile silty and sandy-silty sites of the drained bottom sediments were most intensively overgrown with herbaceous, shrubby and arboreal plants (FIG. 75).

With gradual decrease of water level in the cooling pond, near-shoreline zones were linearly and densely overgrown with herbaceous, shrubby and arboreal plants, due to wind deposition of seeds (in particular, seeds of willows and birches) to pond water surface followed by wind and wave transport of floating seeds to retreating shore lines (FIG. 76A). As a water level gradually decreased, root system of trees developed making groundwater accessible for trees, and allowing them to grow at these sandy sites. Artificially planted for experimental purposes willows [103] also grow well at the drained sandy sites (FIG. 76B).

Elevated sandy areas of the newly formed land (crests) have the least vegetation (which conforms to *a priori* predictions [8]), as these areas are suitable only for growth of xerophytes (FIG. 77A). These sites represent former slopes of the dam, which are formed by washed coarse-grained sands, and are characterized by low contamination levels. Due to coarse lithological composition, coefficient of sediment resuspension with a wind for these sites is quite low, while the rate of dry deposition is high. In this regard, such sites do not pose essential radiological hazard to ChNPP staff members through the external exposure pathway or due to resuspension of radioactive aerosols.

(A) (B) (C)

FIG. 75. Silty and sandy-silty sites of the northern part of the cooling pond drained bottom overgrown with (as in 2017): A) willows (Salix); B) silver birch trees (Betula Pendula), and C) single Scots Pines (Pinus sylvestris) (photo courtesy of V.Kashaparov, UIAR).

(A) (B)

FIG. 76. Former shoreline sites of the drained bottom of the cooling pond being overgrown with willows: A) naturally due to wind transport of seeds to water surface, B) by artificial planting (photo courtesy of of V.Protsak and V.Kashaparov, UIAR).

The same conclusion applies to sandy sites covered with the dead *Dreissena* shells, which do not bear vegetation cover or are only rarely overgrown (FIG. 77B). Specific activity of ^{90}Sr in shells constitutes several thousand Becquerel per kilogram. Such shells however do not pose a radiation hazard from the view point of wind transport and inhalation uptake due to their physical dimensions. A thick layer of shells (up to 50 cm) shields gamma radiation from located below highly contaminated bottom sediments, and prevents wind transport of radionuclides, thereby serving a ‘natural protecting cover’.

FIG. 77. Sparsely vegetated areas of the drained cooling pond bottom (as in 2017): (A) Elevated sandy areas of the newly formed land (crests) and (B) Sandy areas covered by the dead Dreissena shells (photo courtesy of of V.Protsak and V.Kashparov, UIAR).

The silty bottom sediments are usually characterized by the highest levels of radioactive contamination due to their sedimentary genesis, presence of fine dispersed dust particles with high surface area (and respective affinity to radionuclides), and high content of organic matter (up to 50 % of a total weight). As a result of intensive and dense overgrowth of silty sites of pond bottom with vegetation (FIG. 78), the possibility of radioactive aerosols resuspension by wind at these sites is essentially reduced. Presence of dense vegetation (e.g. by 2017 willows in the northern part of the cooling pond have reached a height of 3–4 m) make these sites less accessible for staff members which is also a relevant radiation safety consideration.

FIG. 78. Silty drained pond bottom areas densely overgrown by vegetation (as in 2017) (photo courtesy of of V.Protsak, UIAR).

Based on data of the UIAR, the specific activity of ^{90}Sr and ^{137}Cs in the willow leaves growing in the most contaminated northern part of the drained cooling pond bottom reached about 50 kBq/kg and 20 kBq/kg respectively in 2017. These values are comparable (or even lower) to vegetation contamination levels observed in other highly contaminated areas of the 10 km zone of ChNPP (e.g. at "Red Forest" site).

On the whole the process of the overgrowth of the cooling pond bottom with the vegetation generally conforms to the optimistic forecasts developed in the feasibility study for the ChNPP cooling pond decommissioning [8].

6.2.7. Consequences for aquatic ecosystem of the pond

Based on monitoring studies carried out by the IHB (FIG. 79), main hydro-chemical and hydro-biological parameters of the aquatic ecosystem of the cooling pond remained in 2014–2017 mostly within the sanitary-ecological limits of water quality for meso-eutrophic and eutrophic conditions, which were selected as a reference levels of "ecologically safe" functioning of the pond during the stage of its decommissioning and gradual transformation to the lake-wetland ecosystem (see Appendix IV). On a whole, no "catastrophic" changes of the hydro-chemical and ecological parameters have been observed by 2107, which allowed for continuous water level drawdown regime [102].

In particular, parameters of water transparency, dissolved oxygen, as well as contents of various forms of nitrogen (ammonia, nitrites, nitrates) mostly conformed to the predefined ranges (see some example time series of parameters in FIG. 80, FIG. 81). The exception with respect to a number of parameters was the former 'cold' part of reservoir in summer period of 2017. This was connected with the intensive 'algal blooms', which will be discussed below in more detail.

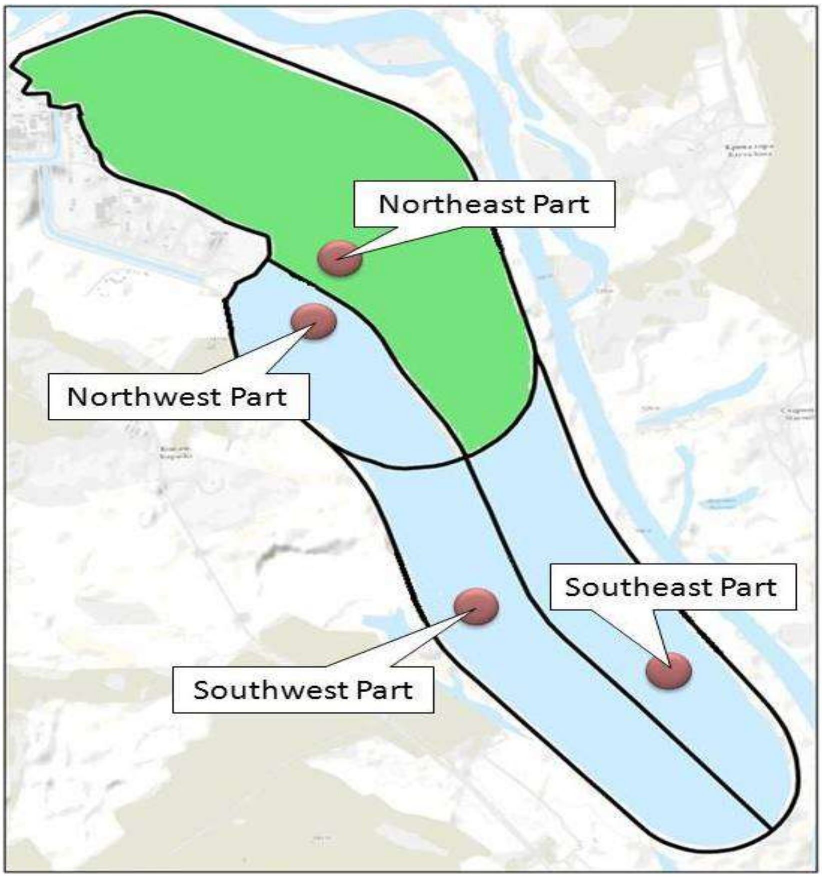


FIG. 79. Sampling points used by IHB to monitor water quality in the cooling pond in the course of its decommissioning. Section impacted by 'algal blooms' in summer 2017 is colored in green.

Due to dewatering of the former littoral areas and forming of the new ones, the dying out has occurred of significant part of former communities of near-shore aquatic plants, zoobenthos and zooperiphython. The number of benthos and fouling organisms has declined compared to previous years.   The role of bivalve mollusks in the ecosystem has decreased significantly.

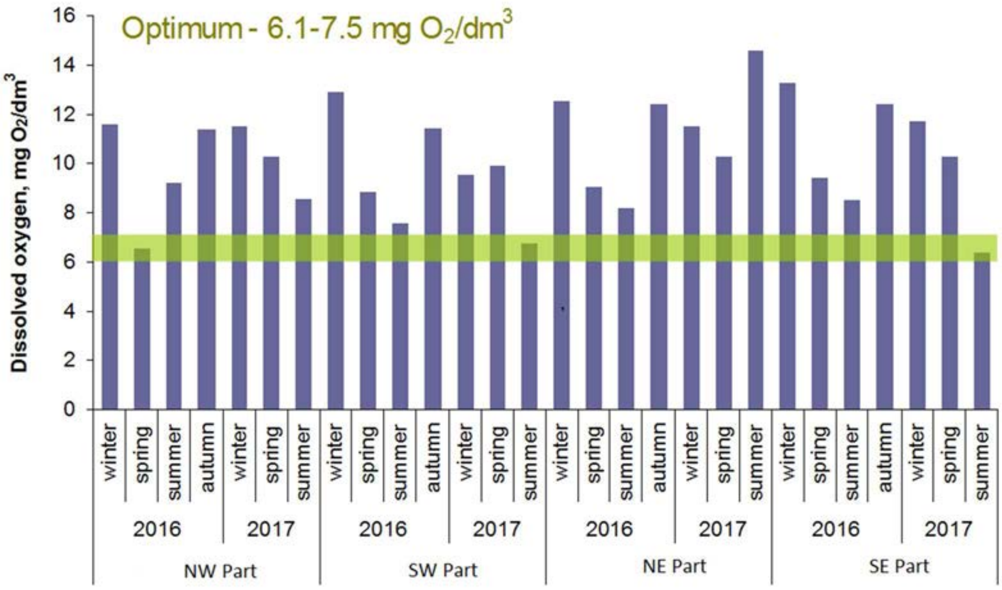


FIG. 80. Seasonal dynamics of the dissolved oxygen in different parts of the cooling pond in 2016–2017 (based on observations of the IHB).

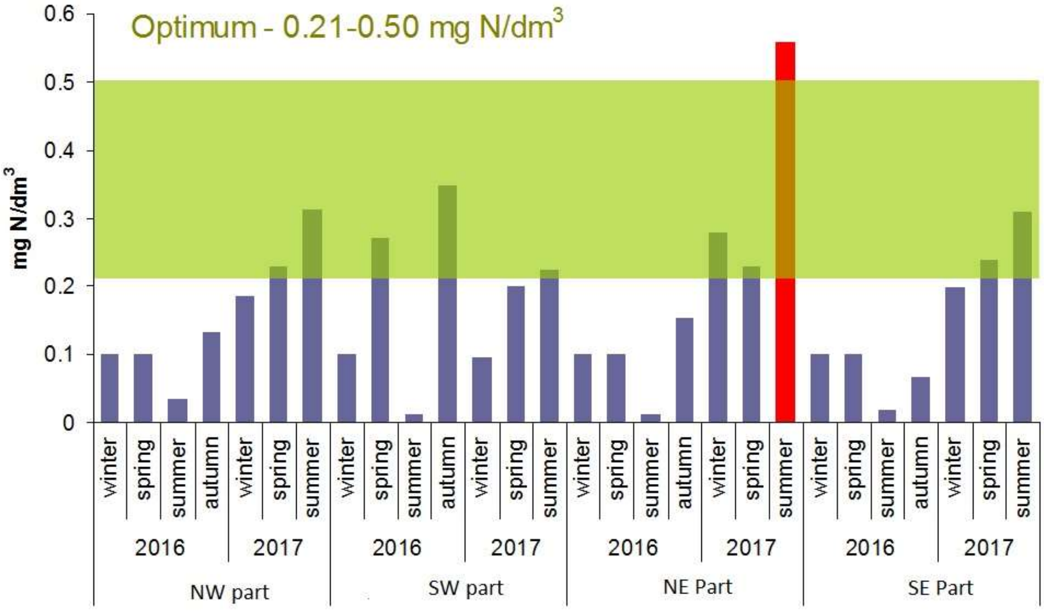


FIG. 81. Seasonal dynamics of the nitrogen (as ammonia) in different parts of the cooling pond in 2016–2017 (based on observations of the IHB).

At present time the invertebrate species, which dominate zoobenthos in some locations, are indicative of process of the eutrophication of the cooling pond. The saprobity index with respect to the invertebrate species of benthos and periphyton corresponds to the β-mesasaprobity zone (eutrophic waters) (FIG. 82).

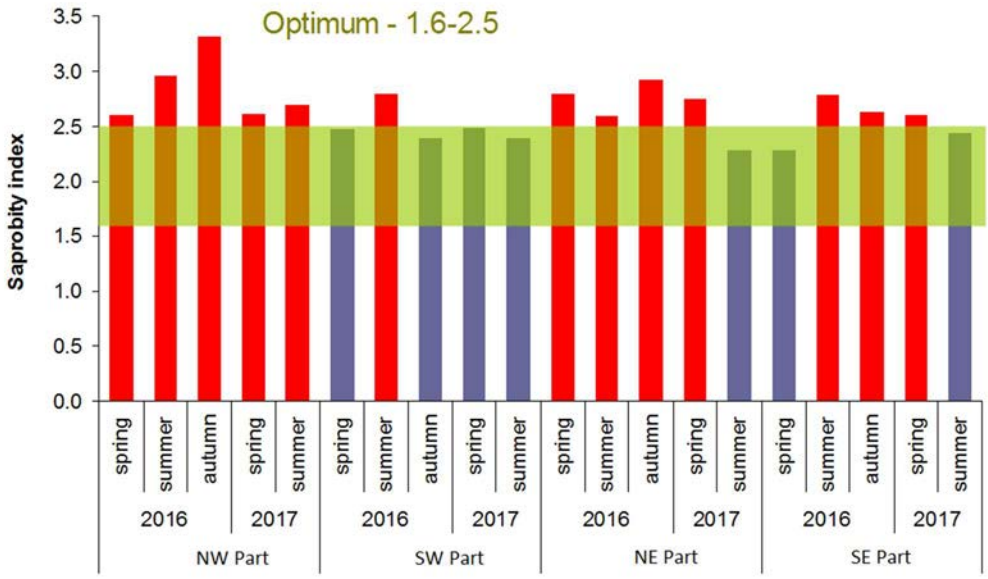


FIG. 82. Seasonal dynamics of the Pantle-Buck saprobity index (with respect to zoobenthos0 in different parts of bottom sediments of the cooling pond in 2016–2017 (based on observations of the IHB).

Contamination of the ecosystem of the cooling pond by organic substances due to dying out of large quantity of higher aquatic plants and zoobenthos of littoral areas (first of all bivalve mollusks) is evidenced also by an increase of parameters of permanganate and bichromate oxidability of aquatic media, especially in spring-summer periods (FIG. 83).

The characteristic peculiarity of water quality in the residual reservoirs of the former cooling pond in summer 2017 was mass development of blue-green algae (cyanobacteria), which have shown much higher vegetation intensity compared to previous years. Based on quantitative parameters of biomass, diversity and structure of dominant species, such mass development of phytoplankton within the water area of the cooling pond can be described as 'algal blooms'. The highest intensity of 'bloom' was observed in the isolated NE part of the pond (FIG. 84), where the number of phytoplankton in the beginning of August 2017 reached 85–200 thousand sp./dm^3.

The species composition of cyanobacteria, which were observed in the cooling pond in summer 2017, fully conformed composition observed during most intensive 'algal blooms' in the reservoirs of the Dnieper River cascade. On average, the majority of indicator species of summer phytoplankton (72%) in residual reservoirs corresponded to 'moderately contaminated' waters [102].

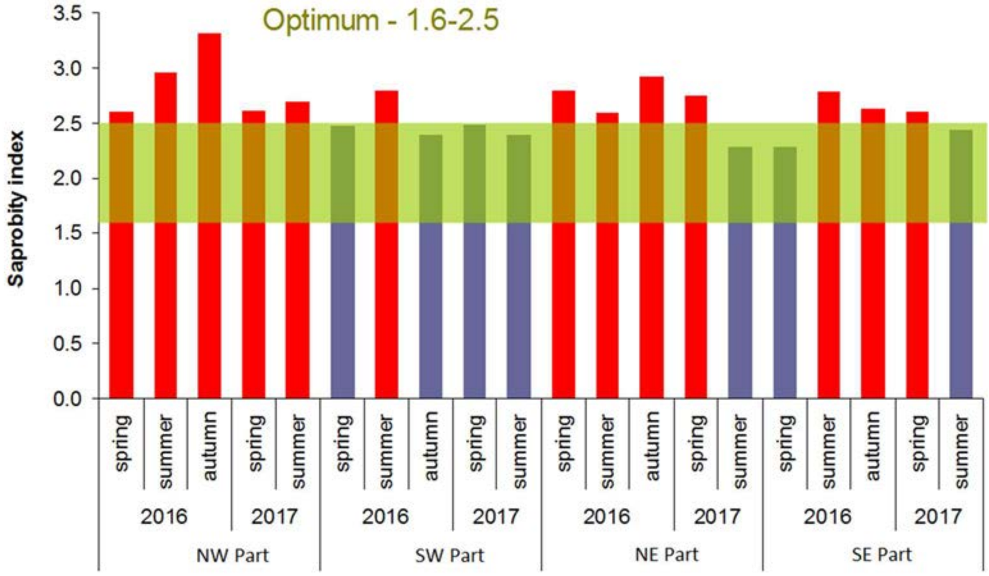


FIG. 83. Seasonal dynamics of the parameter of permanganate oxidability in different parts of the cooling pond in 2016–2017 (based on observations of the IHB).

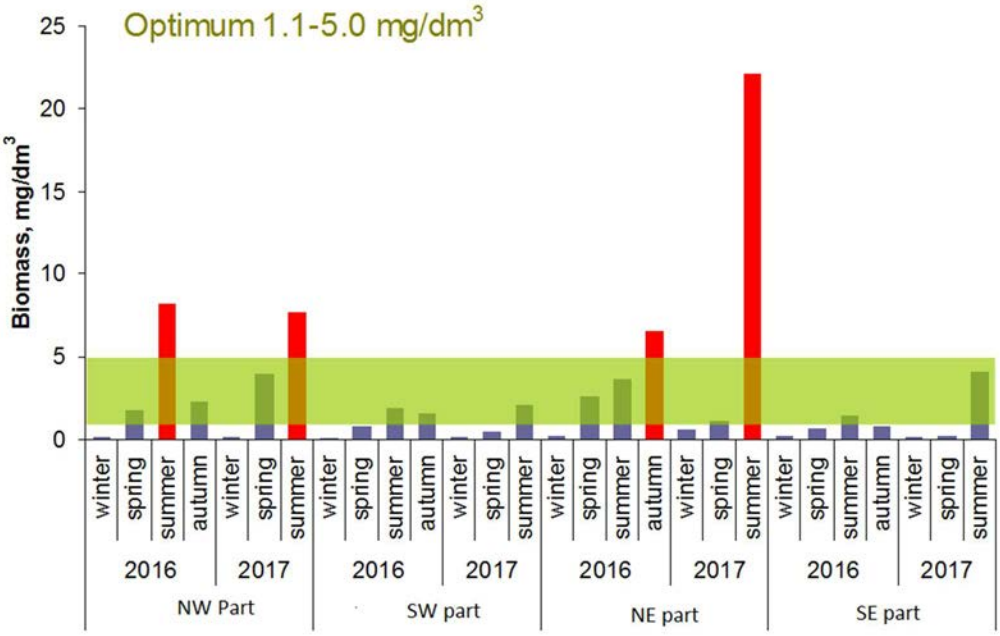


FIG. 84. Seasonal dynamics of the biomass of phytoplankton in different parts of the cooling pond in 2016–2017 (based on observations of the IHB).

6.3. LESSONS LEARNED

The following preliminary experiences from 4 years of cooling pond decommissioning can be summarized:

- Behavior of the cooling pond during the initial phase (4 years) of water level drawdown mostly followed *a priori* expectations and modeling predictions.

- It can be concluded that previous extensive characterization and modeling studies have resulted in generally adequate conceptual understanding of main hydrological, radiological and ecological process and parameters of the cooling pond.

- Good agreement was observed between the modeling predictions and actual data with respect to surface water level drawdown rate in the pond and groundwater level drawdown rates in surrounding areas.

- Radiological impacts from pond were mostly within the prescribed reference (or 'control') levels: in particular, water level drawdown in the pond did not cause resuspension of radioactive aerosols from the drained bottom areas resulting in unacceptable risks to staff of ChNPP and residents of Chernobyl town.

- The dried up bottom sediments with highest levels of radioactive contamination are also those with higher content of organic matter, and they are therefore rapidly overgrown by the newly developing vegetation, which stabilizes the contaminated topsoil layer against wind resuspension.

- No feared catastrophic consequences to the pond ecosystem has been observed so far (e.g. massive dying out of aquatic species leading to deterioration of ecological situation), which allowed for continuous water level drawdown regime.

- Experience of first 4 years also suggests that it would be of interest to develop a better knowledge of a number of end state parameters and process of the cooling pond system.

- The cooling bottom topography reveled in the course water level drawdown has shown some noticeable differences compared to the *a priori* predictions using the 3D numerical model based on bathymetry survey carried out in 2001. The mentioned above inaccuracies may have been caused by a number of reasons, including: sparse measuring grid, sampling point positioning errors, as well as inaccuracies caused by interpolation techniques used (i.e. kriging interpolation).

- Presence in the northern part of the drained pond bottom of small-scale local hot spots with the elevated gamma dose rates (about twice higher than expected) indicates that either these activity hot spots were not captuared by relatively sparse sampling grid of bottom sediment surveys, or these a related to non-conformity of model assumptions on vertical distribution patterns of radioactivity in bottom sediment layer (used in external dose rate calculations) and actual data. Possibility of redistribution of radionuclide activities in the drained bottom areas in the process of water level drawdown in 2014 – 2017 (e.g. by wave action) cannot be excluded as well.

- The fuel particle dissolution process in exposed bottom sediments (based on field experiment) is developing slower than expected presumably due to a low-reactive alkaline geochemical environment and nature of residual fuel particles in bottom sediments (i.e. relatively stable and / or large fuel particles with non-oxidized UO_2 matrix or very chemically resistant matrix incorporating zirconium alloys).

The cooling pond decommissioning is still in its early phase, and it is important to continue and extend the monitoring programme in order to gain maximum information and experience from this ER&D project.

6.4. OUTSTANDING ISSUES

The current stage of cooling pond decommissioning brings to the agenda new issues related to the short-term and long-term assessment and management of this radioactively contaminated site.

For example, the short-term management options considered recently by the ChNPP include re-using (partially) drained area of the pond for establishing solar battery farms. It should be stressed however, that the radiation safety aspects and other technical and economic aspects of such land use have not been thoroughly analyzed yet.

Of interests are also analyses of long-term transport and fate of radionuclides in the cooling pond system, and analyses of related radiological impacts and risks (including on-site risks). The Ukrainian authorities are developing currently the long-term management strategy for the highly contaminated 10 km zone surrounding the ChNPP, including the ChNPP, radioactive waste storage sites, waste processing facilities, contaminated by fallout topsoil hotspots, water bodies etc. One of management options considers creating here a designated ‘industrial zone’ for radioactive waste management, processing and disposal activities.

In this respect, it is of interest to understanding the role of the cooling pond as a source of radioactive contaminants and risks in the context of the 10 km zone, and better understand and assesses long-term restrictions caused by presence of large inventories of radionuclides (including TUE) in the bottom sediments of the cooling pond.

7. SUMMARY AND CONCLUSIONS

The cooling pond of Chernobyl Nuclear Power Plant was seriously contaminated in the course of the Chernobyl accident due to radioactive fallout on the water surface, and due to releases of highly contaminated water from the Unit 4 (water from the reactor emergency cooling system, water used for firefighting, etc.). With time, the main part of radioactive contaminants (^{137}Cs, ^{90}Sr, Pu and Am isotopes) have accumulated in the bottom sediments of the reservoir. The main part of activity inventory in the pond (especially for ^{90}Sr and trans-uranium isotopes) was initially associated with the nuclear fuel hot particles.

Important aspect of the cooling pond problem was that the pond represented a source of ^{90}Sr migration to Pripyat River – Dnieper River system. In addition, as a large hydro-technical object, cooling pond significantly influenced hydrogeological conditions on the whole ChNPP site. In particular, the high water level in the cooling pond created conditions for flooding by groundwater of ChNPP, of Sarcophagus, and of a number of radioactive waste disposal and storage sites situated in its vicinity.

Since early 1990s, a series of international as well as Ukrainian national research projects and remedial feasibility analyses were carried out in order to analyze various aspects of the cooling pond problem, and to develop the strategy and technical approaches for decommissioning and remediation of the cooling pond. Results of these projects, which are reviewed in this report, provided scientific and technical bases for understanding radiological risks caused by the pond and for developing ER&D strategy for this complex radioactively contaminated aquatic system.

With the closure of the ChNPP and shutting down of the last reactor Unit 3 in 2000, there was no need to maintain the cooling pond in its previous volume as a technological cooling water reservoir.

Maintaining the water level in the pond was recognized as not a viable long-term management option, especially due to the need constantly replenish pond with water from Pripyat River by means of pumping station, and related high operation and maintenance cost. There was also a risk of cooling pond dam failure due to geotechnical stability problems.

The drawdown of water level in the pond (in a ‘natural’ or controlled mode) has been identified as an ultimate option for the Chernobyl cooling pond decommissioning. The predicted consequence of the water level drawdown in the pond is dewatering and exposure to atmosphere of highly contaminated bottom sediments. These dried up bottom sediments can potentially represent a source of resuspension and atmospheric dispersion of radioactive aerosols.

The hydrogeological modeling predicted that it will take 3–6 years (depending on climatic conditions) after stopping of replenishing pond with water from Pripyat River for the water level in the pond to drop by 6–7 meters, when it should reach a new “hydrologic equilibrium” conditions.

Risk assessment analyses of consequences of cooling pond level drawdown have shown that:

- Even conservative scenarios of atmospheric resuspension of contaminated bottom sediments result in very low secondary contamination levels of surrounding territory and low inhalation doses to the reference persons (below levels of concern);

- Same conclusion applies to scenario of the wildfire of the dried-up vegetation growing on the contaminated bottom sediments in the drained areas of the pond;

- Though the radionuclide mobility in the exposed bottom sediments may increase following the pond level drawdown due to dissolution of fuel particles (in changed bio-geochemical conditions), the ^{90}Sr transport to Pripyat River will be essentially eliminated due to changed hydrogeological boundary conditions

The potential negative consequences of the cooling pond drawdown apart from atmospheric transport of radioactivity included possibilities for creation of some local “hot spots” of highly contaminated bottom sediments with the elevated gamma dose rate in drained areas. The issue of concern was also “ecological risk” related to possibility of dying out of large amounts of biomass of aquatic organisms, and resulting negative effects of decomposition of the organic substances on water quality of the residual lakes.

Thus, risk assessment studies has confirmed that drawdown of level in the pond is generally acceptable in terms of radiological safety and advantageous with respect to a number of important considerations (e.g. hydrogeological aspects; radionuclide transport to Pripyat River) strategy for decommissioning of the pond. However, identified risks of potential negative radiological and ecological consequences have to be continuously monitored and properly managed in the course of pond level drawdown.

The feasibility study for cooling pond decommissioning completed by Ukrainian scientists in 2013 with support from the IAEA has concluded that “controlled”(or staged) water level drawdown in the pond (regulated by a pumping station) is a preferred decommissioning strategy compared to ‘natural’ (continuous) drawdown under influence of evaporation and seepage losses.

Feasibility analyses have shown that most likely large scale remedial measures for the exposed bottom sediments will not be justified, as off-site risks caused by exposed bottom sediments (e.g. atmospheric transport of radioactivity) are low, while on-site radiological risks are comparable to risks from surrounding contaminated areas.

The cooling pond is situated in so called “near zone” of ChNPP, which is characterized by high levels of radioactive contamination by Chernobyl fallout and has a restricted access. Therefore, the end-state radiological criteria for the decommissioning of the pond were set as a ‘brown field’. These criteria were coherent with the general end-state criteria for the decommissioning of the ChNPP.

The cooling pond decommissioning started in May 2014, when the pond pumping station was switched off, and water level in the pond start to decline due to seepage and evaporation losses.

Due to technological reasons, the water level drawdown in the pond during first 3 years proceeded in a continuous (rather than step-wise or 'controlled') mode. During summer – autumn period of 2014 the water level in Pripyat River was at historically low levels of about 101–102 m a.s.l. Such low levels in Pripyat River did not allow operation of the cooling pond pumping station, as the water level in the receiving chamber was too low.

The monitoring programme carried out in the course of decommissioning has shown that prescribed radiological and ecological parameter reference levels have not been violated in the process of pond bottom drainage, therefore there was no urgent need to interrupt (or suspend) water level drawdown for corrective actions.

On a whole, behavior of the cooling pond during the initial phase (4 years) of water level drawdown mostly followed *a priori* assessments and modeling predictions. Radiological impacts from pond were so far mostly within the prescribed reference (or 'control') levels: in particular, water level drawdown in the pond did not cause increased resuspension of radioactive aerosols from the drained bottom areas. As the dried up bottom sediments with highest levels of radioactive contamination were usually also those with higher content of organic matter, they were rapidly overgrown by the newly developing vegetation, which has stabilized the contaminated topsoil layer against wind resuspension.

No "catastrophic" consequences to the pond ecosystem has been observed so far (e.g. massive dying out of aquatic species leading to deterioration of the ecological situation), which allowed for continuous water level drawdown regime.

Experience of first 4 years also suggests that it would be of interest to develop a better knowledge of a number of end state parameters and process of the cooling pond system (e.g. pond bottom topography, fuel particle dissolution process in exposed bottom sediments, process governing radionuclide speciation and concentrations in water of residual reservoirs, etc.).

The cooling pond decommissioning is still in its early phase, and it is too early for drawing final conclusions. It is important to continue and extend the monitoring programme in order to gain maximum information and experience from this challenging ER&D project.

Decommissioning the cooling pond offers interesting and unique radioecological research opportunities, including studies of process of physical and bio-geo-chemical transformation of nuclear fuel particles and radionuclide speciation in the exposed bottom sediments; study of process governing dynamics of hydro-chemical parameters and related radionuclide dynamics in the water and/or aquatic organisms of residual reservoirs; pond aquatic ecosystem transformation/adaption process, etc.

The experience of monitoring, radioecological research, as well as remedial and decommissioning analyses for the Chernobyl cooling pond can be of broad interest to the scientific and technical community, in particular for developing the ER&D designs for the similar radioactively contaminated sites and aquatic systems.

APPENDIX I

SUMMARY INFORMATION ON THE MAIN PREVIOUS COOLING POND DECOMISSIONING AND REMDIAL PROJECTS

Following table 34 provides the description of the issues addressed in the project by different organizations.

TABLE 34. SUMMARY INFORMATION ON PROJECTS AIMED AT DATA COLLECTION AND DEVELOPING DECOMMISSIONING AND REMEDIAL STRATEGIES FOR THE CHERNOBYL NPP COOLING POND

No.	Study title, organization and report reference	Description of issues addressed by the project
1	Analysis of the environmental protection options in relation to containment of radionuclides in the bottom sediments of the cooling pond and in the floodplain soils of the ChNPP zone; STC KORO, Zhovty Vody [1]	Screening analysis of radiological risks caused by radionuclides contained in bottom sediments of the ChNPP cooling pond, including scenario of atmospheric resuspension in case of pond drainage. Preliminary analysis of technological options for managing of the contaminated bottom sediments
2	Technological Approaches for Decommissioning the Chernobyl Cooling Pond; PNNL, USA [2]	Description of the cooling pond and of the nature and extent of radioactive contamination. Discussion of preliminary modeling and risk assessment results. Defining the Remedial Action Objectives for the cooling pond. Screening of technological solutions for pond remediation based on experience of US projects of a similar nature.
3	PHYTOR: Evaluation of Willow Plantations for the Phyto-rehabilitation of Contaminated Arable Land and Flood Plain Areas; SCK·CEN, Mol [3]	Project evaluated potential of application of the phytoremediation methods (in particular, willow plantation) to remediation (stabilization) of the drained bottom sediments of the cooling pond.
4	Collection and Analysis of Data related to the Contamination of the Chernobyl Cooling Pond; GRS [4]	Compilation of basic information on the ChNPP cooling pond including detailed engineering specifications of the pond. Compilation of data on geology, hydrology, hydrogeology, ecology and radioactive contamination of the pond. Review of radiological problems caused by the pond and possible approaches to its decommissioning and remediation. Definition of main issues to be addressed by the follow up ER&D analysis project. Project included field works on sampling of bottom sediments and groundwater monitoring of the pond.
5	Drawing up and evaluating remediation strategies for the Chernobyl cooling pond; NNC Ltd, UK [5]	Follow up project of the GRS (2000) study. Project works included comprehensive bathymetry survey, characterization of radioactive contamination of bottom sediments and hydrogeological characterization of the cooling pond. Radioactivity inventory in bottom sediments was estimated. Systematic risk assessment analyses of the cooling pond were carried out including groundwater modeling and risk assessment of the atmospheric

No.	Study title, organization and report reference	Description of issues addressed by the project
		transport of bottom sediments for the pond drainage scenario. Systematic analysis and evaluation of remedial strategies for the cooling pond was carried out using the multi-attribute analysis.
6	Radio-ecological study of the Chernobyl cooling pond and options for remediation (RESPOND); CEH, UK [6]	The project focused on radio-ecological conditions of the cooling pond. In particular it analyzed fuel particle dissolution in the cooling pond system, parameters of radionuclide interaction with bottom and suspended sediments, and radioactivity uptake and radiological impacts on fish and aquatic biota. One of important objectives was evaluation of the potential effect of remediation (water level drawdown) on the ecology of the Cooling Pond
7	Ecological justification of possibility of decommissioning of the cooling pond, and compilation of input data for the technical and economic feasibility study (pre-design analyses), Ecomonitor LLC, Kiev [7]	The project represents the pre-design feasibility study for the decommissioning of the cooling pond. It consisted in collection and summarizing data about the cooling pond (environmental conditions, radioactive contamination), and developing the concept for the cooling pond decommissioning by means of water level drawdown (incorporating data and results from previous national and international characterization and pre-design research projects).
8	Technical and economic feasibility study of the decommissioning of the cooling pond of Chernobyl NPP, IPS NPP, Kiev [8]	The project represents the comprehensive official feasibility and EIA study for the decommissioning of the cooling pond prepared in accordance with the relevant Ukrainian regulatory requirements. The feasibility study was prepared by IPS NPP institute (contractor) for the ChNPP (operator of the site). At preliminary phase, the radiological end-state criteria for the cooling pond decommissioning and environmental impact scenarios to be evaluated in EIA report were coordinated by the ChNPP with the regulatory authorities. The report was subject to official review and approval by Ukrainian radiation safety regulatory authorities.

APPENDIX II

METEOROLOGICAL PARAMETERS OF THE CHNPP SITE

Main meteorological parameters of the Chernobyl zone [8] are presented in table 35 and multi-annual average characteristics of wind direction, velocity and frequency as per the record of Chernobyl meteorological station are shown in table 36.

TABLE 35. MAIN METEOROLOGICAL PARAMETERS OF THE CHERNOBYL ZONE [8]

Meteorological parameter	Value
Average yearly temperature	6.6 C
The warmest months of the year and its mean temperature	July, 19 C
Absolute maximum of air temperature	39 C
Absolute minimum of air temperature	-35 C
Duration of the period with air temperature below 0 C	121 day
Duration of the period with air temperature below -5 C	63 days
Dates of transition of the mean day temperatures across 0 C in spring and autumn	20.03–20.09
Mean yearly precipitation	600 mm
Precipitation during the warm season	400 mm
Dates of forming and thawing of the stable snow cover	22.12 – 14.03
Average height of snow cover	17 cm
Depth of soil freezing (mean, maximum)	0.74 m; 1.11 m
Prevailing wind directions (frequency in %)	NW (16), W (15)
Mean annual wind velocity	4.2 m/s
Maximum wind velocity (P 5%)	24 m/s

TABLE 36. MULTI-ANNUAL AVERAGED CHARACTERISTICS OF WIND DIRECTION, VELOCITY AND FREQUENCY (CHERNOBYL METEOROLOGICAL STATION)

Direction	N	NE	E	SE	S	SW	W	NW
Velocity, m/s	3.8	3.0	3.1	3.7	3.7	3.8	4.0	4.2
Frequency, %	7	9	9	13	6	18	15	23

APPENDIX III

AQUATIC ORGANIZMS IN THE COOLING POND

This Appendix summarizes results of studies of the aquatic habitat of the cooling pond carried out by the by the Institute of Hydrobiology (IHB) of the National Academy of Sciences of Ukraine in 2012–2013 [25].

III.1. MACROPHYTES

According to the results of geobotanical studies of the reservoir in 2003 [104], the higher aquatic plants were spread within the area about 292 hectares, of which 23 hectares of the coastal water area were populated by emergent plants, and 269 hectares by submerged plants. According to the results of the same study, green filamentous algae covered about 27 hectares of the pond. Emergent plants were spread mainly to depths of 1.0–1.2 m, and submerged plants and filamentous algae were spread at depths to 4.0–4.5 m. The phytomass of emergent plants was evaluated to be 837 tons, and the masses of submerged plants and filamentous algae were evaluated to be 100 tons and 7 tons respectively. The studies by the Institute of Hydrobiology (IHB) of the National Academy of Sciences of Ukraine in 2012–2013 revealed 17 species of macrophytes of 13 families (*Poaceae, Typhaceae, Araceae, Iridaceae, Butomaceae, Halorogaceae, Ceratophyllaceae, Najadaceae, Potamogetonaceae, Nymphaeaceae, Hydrocharitaceae, Lemnaceae, Salviniaceae*) in the cooling pond.

The common reed (lat: *Phrágmites*) cenosis—of emergent plants surrounded the coastal area of the cooling pond practically along the whole perimeter. The width of the brushwood strip of emergent plants varied from 1 m (along the current-guiding dike with relatively steep slopes) to 30 m and more (within the pond shallow areas—water less than 1 m depth, for example along the northern and eastern sectors of the cooling pond dam). The average width was 6–12 m. The common reed height may reach 1.5–3.9 m, and the density may reach from 68 to 456 sprouts per m^2.

The results of the evaluation of the reed phytomass and filamentous algae during the vegetation period of 2013 are summarized in TABLE 37.

TABLE 37. PRODUCTION CHARACTERISTICS OF MACROPHYTES IN THE COOLING POND IN 2013 [25]

Macrophyte species	Growing area (hectares)	Phytomass (tons of air-dry mass)	Production (tons/year of air-dry mass)
Emergent plants	39	1870	2244
Submerged plants	36	51	204
Filamentous algae	7	7.6	76

III.2. ALGAE

Vegetation, including floating leaves and floating loose plants, is not significantly spread across water surface of the cooling pond, except for some small shallow areas in northern (former 'cold' area) part of the cooling pond. According to the data collected by scientists of the IHB, prior to the Chernobyl accident and during the initial post-accident period over 300 species of algae were present in the cooling pond.

Green (mainly protococcal) diatomaceous and blue-green algae prevailed. In 2012–2013, 154 species of algae of different taxonomic groups were identified. In the past years, much diversity pertained to diatomaceous algae (53% of total taxonomic diversity), green (27%), and blue-green algae (16%).

The 129 species of periphyton and 90 species of epiphyton were identified in the cooling pond. Biomass of phyto-fouling of emergent plants (*Phragmites australis*) during vegetation seasons varied from 2.1 to 126 mg/g of aero-dry mass. Biomass of epiphyton of submerged plants was estimated to range from 19 to 146 mg/g of aero-dry mass. Hydro-biologists used these data to assess an approximate inventory of fouling by emergent plants which yielded up to 10 tons of wet biomass and about 8 tons for submerged plants (in total up to 18 tons of wet mass). At the time the survey, the total mass of phytofouling did not exceed 0.1% of the total aero-dry mass of macrophytes.

The main substrates for periphyton are stone piles of the submerged part of the dam slopes of the cooling pond to a depth of about 1 m. The total mass of periphyton was evaluated to be up to 2 tons of wet mass, which corresponds to less than 0.2 tons of air-dry mass or only 0.01% of the total inventory of macrophytes.

At the same time, taking into account high production of phytofouling during the vegetation period, phytoepiphyton of air-aquatic plants may generate up to 3,700 tons of wet biomass per year, and phytoepiphyton for submerged plants and periphyton - about 2,950 and 740 tons per year, respectively. The total biomass that may form fouling algae was evaluated up to 7,400 tons per year for wet biomass or approximately up to 700 tons if recalculated for air-wet mass.

III.3. PHYTOPLANKTON

The species of phytoplankton in the Cooling Pond are highly diverse. Earlier published data have shown that the wet biomass of phytoplankton during different seasons was evaluated to range from 3 to 130 g/m^3. An average biomass during the vegetation period and the average annual biomass were estimated to be 47 g/m^3 and 31 g/m^3, respectively. The 2012–2013 studies revealed 23 species of phytoplankton. Among them the dominant were blue-green, Euglena, diatomaceous and green algae, which corroborates with the early research. The total biomass of phytoplankton in the cooling pond during the vegetation period of 2012–2013 was assessed between 183 and 418 tons. Based on the data collected by the IHB researches, during vegetation period of 2012–2013 phytoplankton formed wet biomass from 66 to 150 tons per year.

III.4. INVERTEBRATE

Zooplankton

Early studies along with the data collected in 2013 showed that the cooling pond was characterized by extremely high diversity of invertebrate (zooplankton and zoobenthos). The structure of zooplankton was mainly composed of plankton fauna typical for lake ecosystems. Biomass of zooplankton was on average 0.3–1 mg/l during the vegetation period. At one of the monitoring stations, there were identified from 23 to 29 species of zooplankton, and at another station from 15 to 28 species.

Zoobentos

Zoobenthos in the cooling pond was characterized by significant diversity, and was presented mainly by larvae of *Chironomids*, *Oligochaetas*, *Gammaridaes* and soft benthos and mollusks of different species, with prevailing of *Dreissena* colonies. During the operation of the ChNPP, the total biomass of *Dreissena* at the water inlet channel and dams in the areas not impacted by discharge of heated water was 2,500 tons. The maximal biomass density of *Dreissena* detected in the inlet channel was up 20 kg/m^2.

In 2012–2013, the density of *Dreissena* was maximal at relatively shallow (less than 2 m) parts of the reservoir, where the biomass density (excluding mollusks' shells) reached 4–5 kg/m^2. Residual shells of *Dreissena* were observed within many parts of reservoir bottom.

Zoobenthos groups had polydominant structure, including *Oligochaetes, Larvae of Chironomids, Hydra, Ostracods Cancers, and Gammarids.* The total biomass was determined mostly by 22 zebra mussel, and the biomass of 'soft' zoobenthos by *Gammarids, Korofiidy, Oligochaetes, and Larvae of Chironomids*. The main substrate for zooperiphyton in the pond is the slope of dam to a depth of about 3 m.

In 2012–2013, the total zoobenthos biomass in the Cooling Pond to 7 m depths increased in comparison with early data at the former 'warm' part of the reservoir it was about 5,662 tons, and in the former 'cold' part about 11,260 tons, in total up to 16,920 tons, and shells and organic substances about 5,076 tons of wet mass.

Zooperiphyton

Based on surveys in November 2012 and May 2013, the total biomass of zooperiphyton in cooling pond was estimated to range from 3,000 to 4,000 tons of wet mass.

III.5. FISH

Prior to the Chernobyl accident, there were 33 species of fishes related to 7 families in the cooling pond, including 19 species in minnow (carp) family, and only 1–2 species in each of several other families of perch, catfish, pickerel, etc. Majority of fish species entered the cooling pond from the Pripyat River, as well as from the floodplain lakes during the pond construction. Some fish species (white and motley silver carp, channel catfish, trout, and bigmouth buffalo) were introduced in the cooling pond in 1983–1985 with the purpose of fish breeding. Because no detailed evaluation of current status (as in 2013) of species of fish communities in the cooling pond has been conducted, the current review is based on the data collected in 1994–1998. Based on the expert evaluation of the fish species diversity, the biomass density of fish in the cooling pond ranged from 250 to 750 kg/hectare, and the total fish biomass ranged from 500 to 1500 tons. A substantial part of the fish population is expected to perish during the decrease in the water level in the pond. At present, it is difficult to forecast expected changes in fish biomass and diversity.

APPENDIX IV

REFERENCE SANITARY-ECOLOGICAL PARAMETERS OF WATER QUALITY IN THE COOLING POND IN THE PROCESS OF DECOMMISSIONING

Parameters of water quality and the range in the cooling pond during the process of decommissioning are described in table 38.

TABLE 38. REFERENCE SANITARY – ECOLOGICAL PARAMETERS OF WATER QUALITY IN THE COOLING POND IN THE PROCESS OF DECOMMISSIONING [8]

Parameters	Recommended range of values
Hydro-physical	
Transparency of water	$\geq$ 0.65 m
Suspended matter	11–20 mg/dm^3
Hydro-chemical	
pH	6.5–8.3
Nitrogen (ammonia)	0.21–0.5 mg N/ dm^3
Nitrogen (nitrites)	0.006–0.001 mg N/ dm^3
Nitrogen (nitrates)	0.31–0.5 mg N/ dm^3
Phosphorus (phosphates)	0.0031–0.1 mg P/ dm^3
Dissolved oxygen	6. 1–7.5 mg O_2/ dm^3
Saturation by oxygen	71–130%
Permanganate oxidability	5.1–10.0 mg O/dm^3
Bichromate oxidability	16–30 mg O/dm^3
Hydro-biological	
Biomass of phytoplankton	1.1–5 mg/dm^3
Index of self-purification – self/contamination (A/R)	0.8–1.5
Bacteriological	
Number of bacteria-plankton	1.6–2.5 million/ dm^3
Bio-indication of saprobity (indices of saprobity)	
Pantle-Buck (phytoplankton and zoo-benthos)	1.6–2.5
Pantle-Buck (zoo-plankton)	1.6–2.0
Goodnight - Whitley	46–70

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ABBREVIATIONS AND ACRONYMS

AMAD	Activity Median Aerodynamic Diameter
BIOMOVS	Biosphere Model Validation Study
ChEZ	Chernobyl Exclusion Zone
ChNPP	Chernobyl Nuclear Power Plant
DEM	Digital Elevation Model
DOE	Department of Energy
ECOMONITOR	Centre of Monitoring Studies and Environmental Technologies, Kiev
EDR	Exposure Dose Rate
EED	Effective Equivalent Dose
EIA	Environmental impact Assessment
ER&D	Environmental Remediation and Decomissioning
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
IGS	Institute of Geological Sciences, Kiev, Ukraine
IHB	Institute of Hydro-Biology of the Ukrainian National Academy of Sciences
IPS NPP	Institute of Problems of Safety of Nuclear Power Plants of the Ukrainian National Academy of Sciences
ISTC	Inter-disciplinary Scientific and Technical Center "Shelter",
KSU	Kiev State University
MEU	Ministry of Emergencies of Ukraine
MHU	Ministry of Health of Ukraine
NPP	Nuclear Power Plant
NORM	Naturally Occurring Radioactive Materials
PK	Reference coordinate mark (concrete post) called "picket" along the dam of the cooling pond

R&D	Research and Development
RWDS	Radioactive Waste Disposal Site
RWTSP	Radioactive Waste Temporary Storage Points
SCU	Supreme Council of Ukraine
SHI	State Hydrological Institute, St Petersburg, Russia
SLIRT	Slavutich Laboratory of International Research and Technology
SNRIU	State Nuclear Regulatory Inspectorate of Ukraine
STC KORO	Scientific and Technical Center on Complex Treatment of Radioactive Wastes, Zhovty Vody, Ukraine
TRU	Transuranic radionuclides

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19-00781

International Atomic Energy Agency
Vienna
ISBN 978–92–0–161619–7
ISSN 1011–4289