Groundwater contamination following the Chernobyl accident: overview of monitoring data, assessment of radiological risks and analysis of remedial measures

Dmitri Bugai
Institute of Geological Sciences (IGS), Kiev, Ukraine

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Outline

- Introduction: Sources of groundwater contamination, Chernobyl Site hydrogeology
- Overview of groundwater monitoring data
- Review of post-accident remedial measures
- Risks from groundwater contamination
- Natural attenuation process in groundwater (data from 2001-2010)
- Lessons learned (having in mind Fukushima Daiichi Accident)
1.1 Terrestrial contamination by $^{137}\text{Cs}$ in the vicinity of ChNPP
1.2 Sources of groundwater contamination

Radiologically important Chernobyl contaminants are: cesium-137, strontium-90, plutonium-239, 240, and americium-241

Strontium-90 has shown highest mobility in soils and groundwater; intensive migration to groundwater became evident in 1988-1989

Main sources of groundwater contamination:
- Radioactive fallout (“diffused source”)
- Sarcophagus (damaged Unit 4 of ChNPP)
- Radioactive waste dumps (“Red Forest”…)
- Cooling pond of ChNPP

Strontium-90 concentrations in groundwater in the near zone of ChNPP in 1998 [data of IGS]
1.3 ChNPP site hydrogeology

Hydrogeology conditions in Chernobyl zone generally favor radionuclide migration to groundwater:

- Humid climate (annual precipitation ~600mm)
- Flat landscape
- Local sandy deposits have relatively high permeability and low adsorption capacity; soils are slightly acidic

Geological cross-section of Chernobyl Exclusion Zone
[A.Matoshko, 1999]
2.1 Groundwater contamination cause by diffused pollution of the ChNPP Site by radioactive fallout

Typical ranges of radionuclide activity in groundwater at ChNPP Site:

$^{90}\text{Sr} - \text{n} * 10 - \text{n} * 0.1 \text{ Bq/l}$

$^{137}\text{Cs} - \text{n} * 0.1 - 0.01 \text{ Bq/l or less}$

$^{239,240}\text{Pu} - \text{n} * 0.001 \text{ Bq/l or less}$

Groundwater monitoring data for well no. 14-III ("Kompleksny" Site; 1988-2001) [EcoCenter data]

Groundwater monitoring data for well no. K-5 ("Nefebaza" Site; 1990-2001) [EcoCenter data]

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3.2 Groundwater contamination in the vicinity of Sarcophagus

Maximum radionuclide concentrations in groundwater [NNC, 2001]

$^{90}\text{Sr}$ - 3800 Bq/l

$^{137}\text{Cs}$ - 200 Bq/l

$^{239,240}\text{Pu}$ - 7 Bq/L

High $^{137}\text{Cs}$ activity in groundwater can be related to leakage of highly contaminated cesium enriched water ($^{137}\text{Cs}$ activity of ~0.1 – 50 MBq/L) from the basement premises of Sarcophagus

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3.3 Experimental site (EPIC) at Red Forest waste dumps (IGS – UIAR – IRSN, 2000-2012)

ChNPP site map

monitoring well cluster

Pit for unsaturated zone monitoring

Chernobyl database

monitoring data

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3.4 Elements of monitoring system at EPIC site in Chernobyl Red Forest

On-site laboratory module

Station for unsat. zone monitoring

Monitoring wells

Meteorological station
3.5 Groundwater contamination at “Red Forest” waste dump site

\( ^{90}\text{Sr} \) distribution in the aquifer cross-section at Trench no.22 (2002)

- In-situ \(^{90}\text{Sr} \) retardation factor: \( R \sim 14 \) (7% of GW flow velocity)
- \(^{90}\text{Sr} \) Kd values from field tests: 0.5-2 L/kg (for eolian sand deposits)

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3.6 $^{137}$Cs migration behavior in soils and groundwater

- Regional groundwater monitoring system in Chernobyl zone usually reports $^{137}$Cs concentrations of n×0.01 - n×0.1 Bq/L
- In general $^{137}$Cs shows low mobility in mineral soils of Chernobyl zone

- $^{137}$Cs concentrations in groundwater of Red Forest ranged within n×0.1 - n×1 Bq/L
- $^{137}$Cs sorption Kd-s from lab batch tests are 100-170 l/kg; $^{137}$Cs retardation factor from column test is R=6600 [S.Szenknect 2003]

Main factors controlling $^{137}$Cs migration in soil profile:
- radionuclide fixation by clay minerals, sorption by ion-exchange;
- biogeochemical RN cycling in “soil – plant” system;
- water regime of soils;
- radioactive decay

Dynamics of ion-exchangeable forms of $^{137}$Cs in soddy-podzolic soils following Chernobyl accident
Effective “half-life” for fixation $T_{1/2}$ is 0.8 – 1.4 years (first 5 y) [Ivanov and Kashparov, 2003]

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4.1 Post-accident groundwater remedial measures

Governmental Decree on groundwater protection measures was adopted on 30 May 1986

Urgency of remedial measures was dictated by the potential threat from the hydrological river transport of fall-out radionuclides to the Ukrainian capital Kiev and other downstream populations (9 million pers. using Dnieper water);

One other concern was protection of local water supply wells (exploiting the Eocene aquifer)

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5.2 Lessons from inefficient emergency remedial measures

Groundwater remedial measures were based on incomplete knowledge and the “worst case” analysis (…assumed maximum solubility of fallout; maximum fallout densities; minimal retardation…)

Based on monitoring data and updated radioactivity survey data by the end of 1986 the groundwater remediation projects were stopped.

Only 2.2 km of the initially planned 8.5 km of the slurry wall barrier were completed.

The protective drainage systems were put on reserve (the equipment being later dismantled)

The “payment “ for overconservative remedial assessments were:
- High and unnecessary remediation costs (e.g., cooling pond drainage system cost was 22 mill. rubles);
- unnecessary exposures to mitigation workers (the exposure rates at ChNPP in the summer period of 1986 were about 0.001 – 0.01 Sv/h).

Mistakes in emergency remedial measures resulted from:
- lack of reliable radiological information and assessment models;
- absence of criteria for decision making regarding a need for remediation;
- absence of peer review by independent experts

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6.1 Risks caused by groundwater contamination

Off-site risks

• Projected max. $^{90}$Sr release rate from the ChNPP Site is approx. $\sim 0.1$ TBq/y or 0.02% per year from initial watershed inventory
• Surface water transport of $^{90}$Sr (~10-20 TBq/y in 1989-1991) was dominated by wash-off of radionuclides from floodplains and from wetlands
• Water pathway contributed only 6% of dose to the resident of Kiev Region (in 1993); doses induced by water pathway are estimated at $10^{-2}$-$10^{-3}$ mSv/y [Berkovsky et al., 1993]

On-site risks

• On-site radiological risks for hypothetical residents in Chernobyl Zone are dominated by risks caused by surface contamination [Bugai et al., 1996]
• Probabilistic analysis has shown low risk of contamination of water wells exploiting Eocene aquifer [Bugai and Smith, 1996]
6.2 Modeling predictions of $^{90}$Sr in groundwater transport from “Sarcophagus” [Kivva, Zhelaznyak, 1997]

- $t=100$ y
- $t=1000$ y

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6.3 Modeling predictions of $^{90}$Sr transport in groundwater from Red Forest waste dumps [Bugai tal., 2012]

Predicted long-term $^{90}$Sr transport in the aquifer from Trench no.22 at Red Forest Site

Modeling results:
- The maximum distance of $^{90}$Sr migration from the waste site in conc. >2 Bq/L ($^{90}$Sr drinking standard in Ukraine) constitutes 200 m;
- The aquifer is contaminated to the depth of about 15 m;
- In about 250 a $^{90}$Sr concentrations throughout the aquifer will decrease below 2 Bq/L

Conclusion:
Red Forest waste site does not pose risk of contamination of Pripyat River
6.4 Water protection measures in Chernobyl zone in 1990-2000

Based on prioritization of contaminant sources and modeling analyses, in later period (1990-2000) water protection measures focused on isolation of floodplain areas of Pripyat River in the vicinity of ChNPP contaminated by fallout radionuclides.

The current recommended strategy for contaminated groundwater is monitored natural attenuation (MNA).

Protective dikes isolating contaminated floodplain areas of Pripyat River in the near zone of ChNPP.

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7.1 Natural attenuation process in groundwater: Geochemical regime of the aquifer at “Red Forest” waste dump site

Mean $^{90}$Sr plume concentration 1997-2001

Mean $^{90}$Sr plume concentration 2002-2008

Increase of $^{90}$Sr caused by flooding by groundwater of trench bottom in May-June 2005

Mean NO$_3$ plume concentration 2004-2008

Mean Ca plume concentration 1998-2002

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7.2 Conceptual bio-geochemical radionuclide migration model for the “Red Forest” waste dump site

- **Biogenic flux:**
  - $0.82\%$ a$^{-1}$ from trench inventory in 2005
  - [Thiry et al., 2009]

- **Geo-migration:**
  - $0.14-0.5\%$ a$^{-1}$ (1987-2000) [Bugai et al., 2001]


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7.3 Natural attenuation process in groundwater of “Red Forest”

Evolution of $^{90}\text{Sr}$ migration fluxes from trench no.22T in 1988-2008

- **1988**: $\text{Ca} > 40 \text{ mg/L}, \ V_{90\text{Sr}} > 2.5 \text{ m/a}$
- **1998-2000**: $\text{Ca} = 20 \text{ mg/L}, \ V_{90\text{Sr}} \sim 0.7 \text{ m/a}$
- **2006-2008**: $\text{Ca} = 5-10 \text{ mg/L}, \ V_{90\text{Sr}} \sim 0.1 \text{ m/a}$

“Biogenic” factors contributing to natural attenuation in GW: - direct RN uptake by vegetation and incorporation to biological cycle; - nutrient element (Ca,K…) uptake by vegetation, which influences GW geochemistry and hence - RN mobility

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8.1 Lessons learned (assessment of risks and remedial planning)

- Assessment for remedial activities must *use realistic analyses and incorporate best science*

- **Remediation criteria and objectives** should be clearly defined early in the assessment phase of groundwater remedial activities.

- Groundwater contamination problems should be considered within the “*big picture*” of various radionuclide exposure pathways and risks
  (… Decision-makers and ordinary public often suppose that groundwater contamination entails much higher risk than it really does)

- **A peer review of proposed actions** is important

- Adequate modeling of long-term radioactive contaminant transport in unsaturated zone and groundwater requires *integrated ecosystem* approach
8.2 Chernobyl lessons learned: Diagram of the terrestrial radioecological model knowledgebase components

THANK YOU FOR YOUR ATTENTION!