Groundwater Monitoring in the Chornobyl Exclusion Zone - Challenges, Lessons Learned, and the Path to Modernization

Dmitri Bugai

National Academy of Sciences, Kyiv, Ukraine

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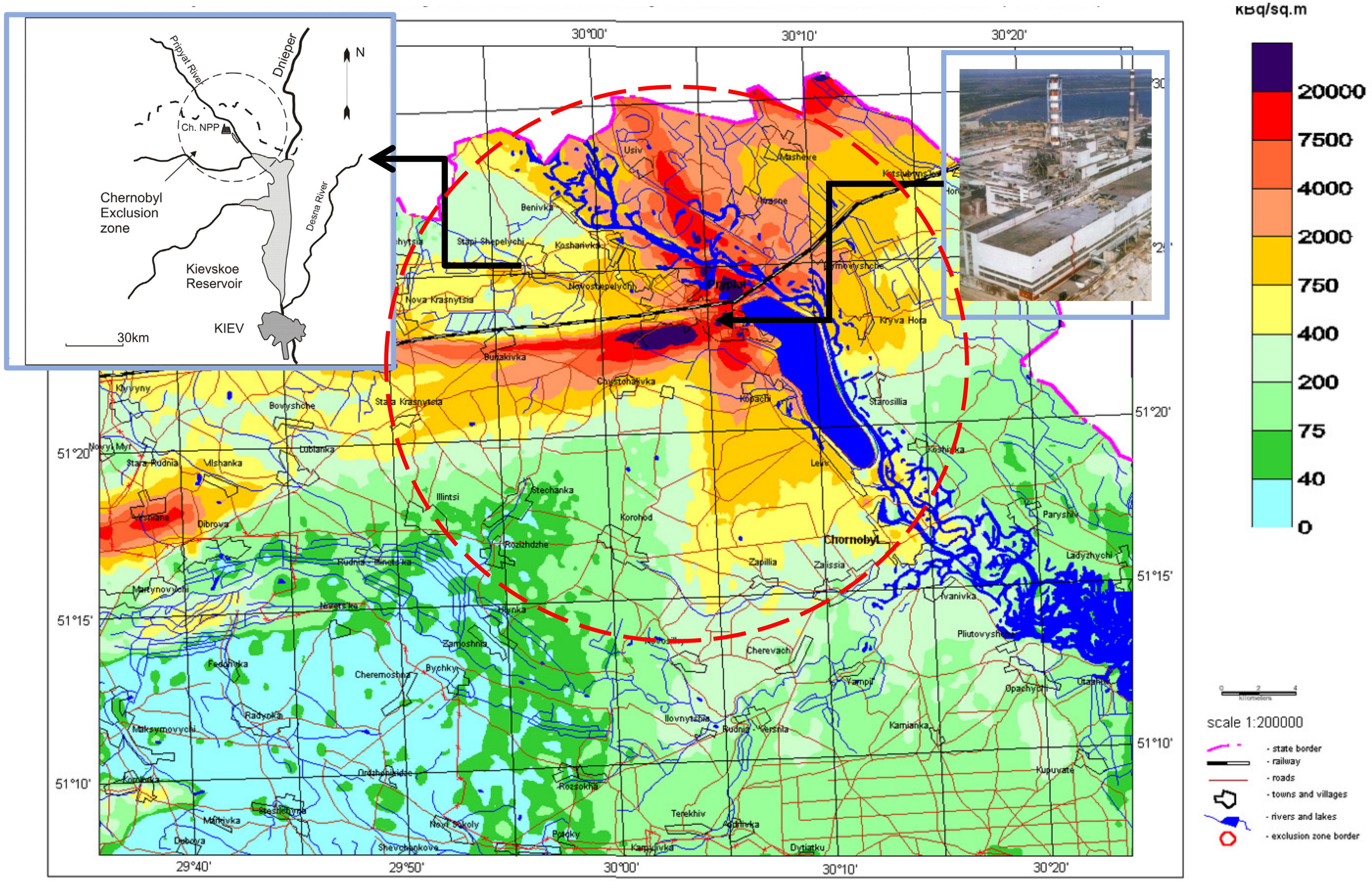
2. Chornobyl Exclusion Zone–geography and radionuclide inventory

- Chornobyl Exclusion Zone (CEZ, 2600 km^2) was established shortly after the 1986 Chornobyl Accident;
- CEZ contains fallout radionuclides mostly in the fuel particle form;
- The most highly contaminated part of CEZ is the 10-km zone of ChNPP;
- The contaminated area is situated in the upper reaches of the Pripyat-Dnieper River basins, with the potential of off-site transport of radioactivity to downstream populations.

Map of the Chernobyl Exclusion zone and ^{137}Cs contamination (as of 1997)

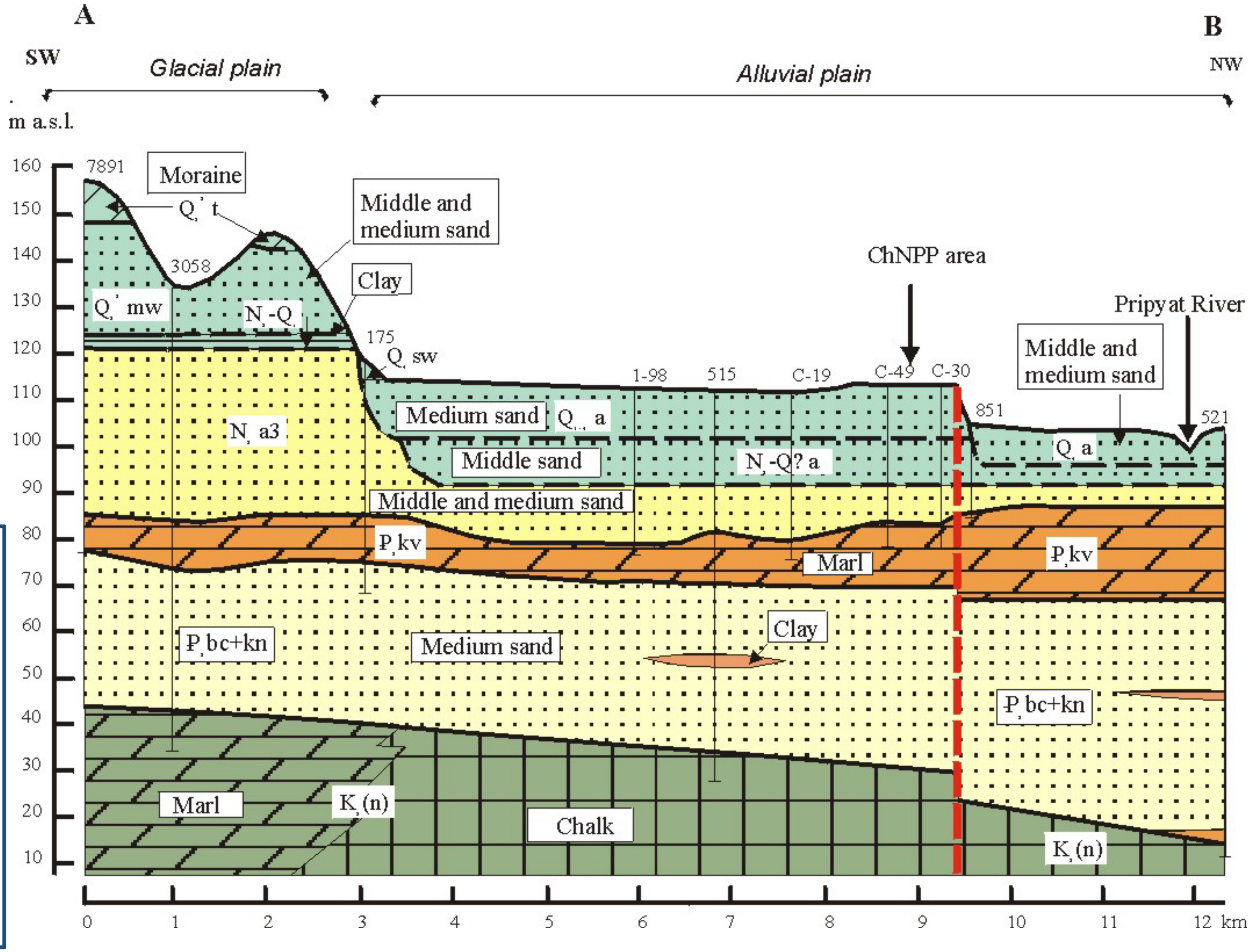


3. Chornobyl Exclusion Zone climate, geology, and hydrogeology

Environmental conditions

- Humid continental climate (rainfall ~600 mm/y);
- Relatively flat landscape;
- Shallow groundwater table (often 1-3 m or less);
- Sandy alluvial and fluvioglacial deposits have relatively high permeability and low CEC;
- Groundwater recharge rates 100–250 mm/y; flow velocities ~ 10 m/y.

Geological cross-section of CEZ



Adapted from [Matoshko, 1999]

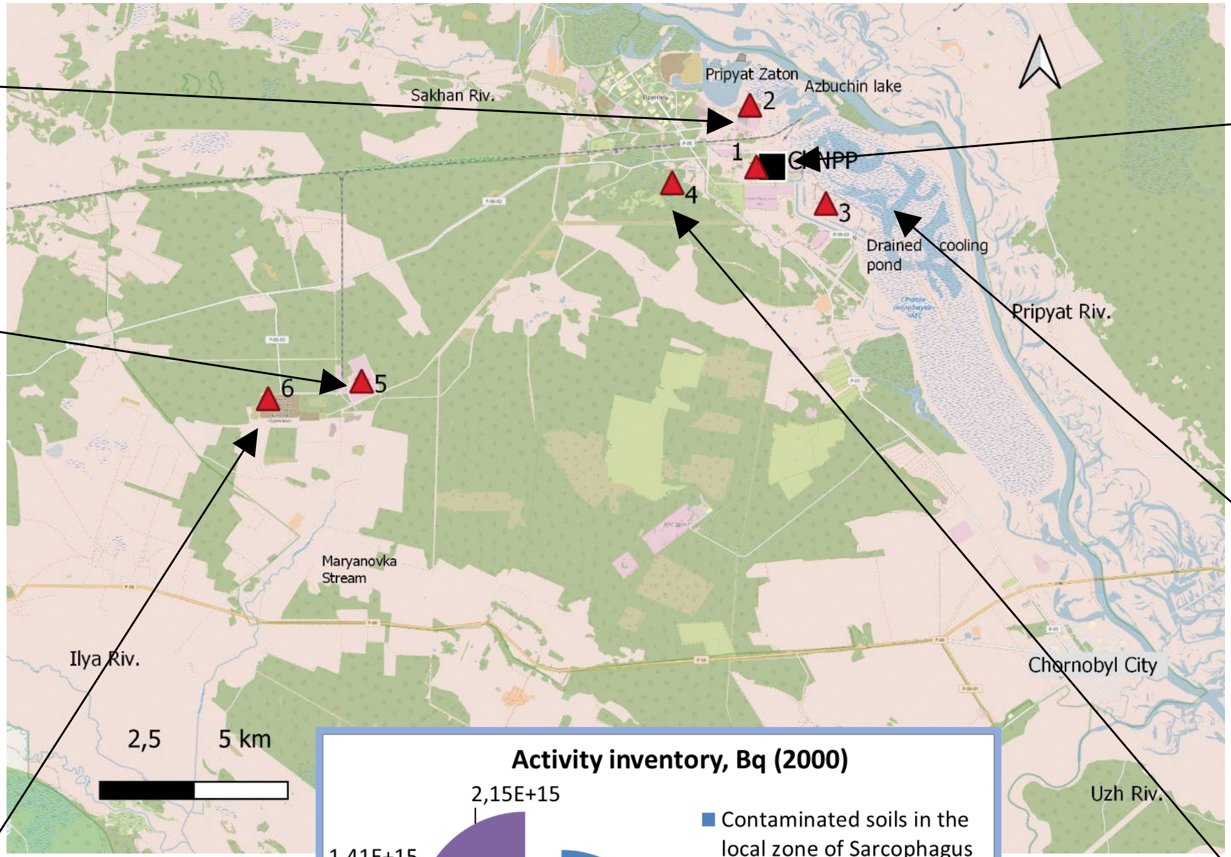
- Hydrogeologic conditions generally **facilitate radionuclide migration into groundwater**.
- From the earliest days following the accident, the **transport of radionuclides via groundwater to the river network**—and ultimately to downstream populations in the Dnieper Basin—**was recognized as a major hazard**.

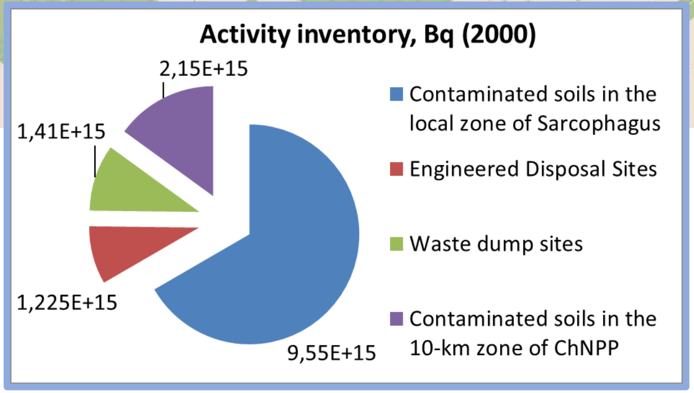
4. Sources of radioactivity in the Chornobyl Exclusion Zone

"Pidlisny" HLW Storage Site

Complex "Vector"

"Buryakivka" Waste Disposal Site





New Safe Confinement (Unit 4)

Cooling pond (drained)

"Red Forest" Site

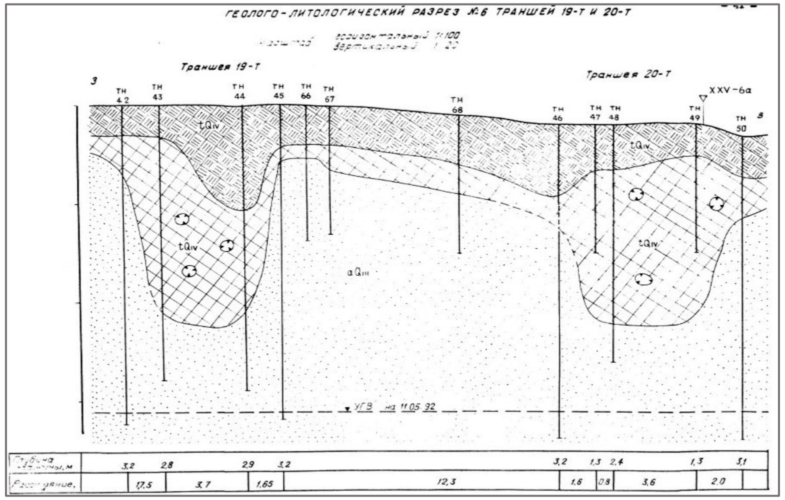
5. “Red Forest” waste trenches

• Waste trenches were created at ChNPP site in 1987 by civil defense troops to mitigate risks of forest fire in dead “Red Forest” (killed by extreme radiation levels) and to reduce external exposure to “liquidators”;

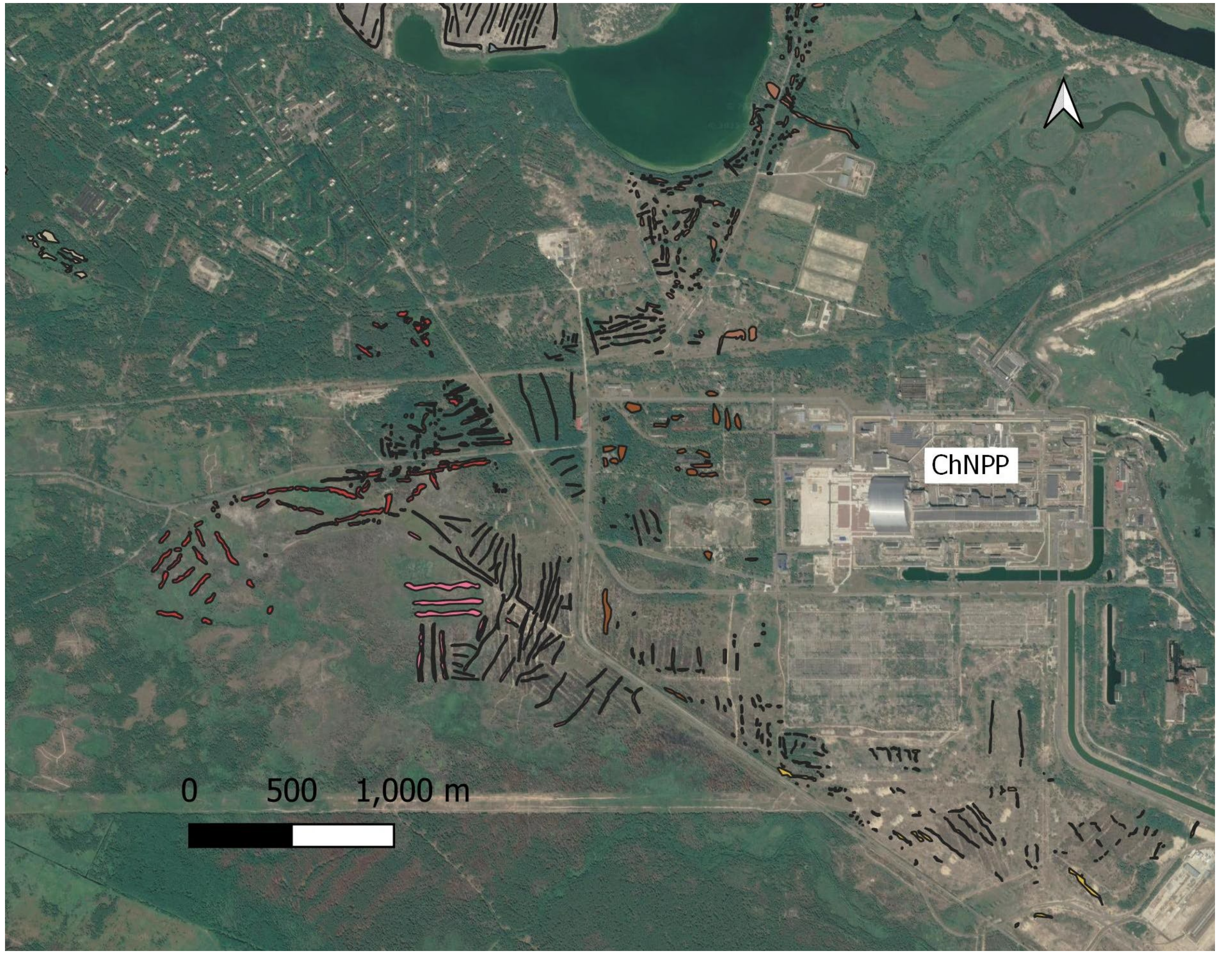
•The total area of clean-up was **~ 12 km²**, with hundreds of individual waste burials, and the total amount of buried waste **~ 1 mill. m³** ;

• These trenches became with time sources of **serious contamination of groundwater** by radionuclides, especially by strontium-90.

Cross-section of the waste trench



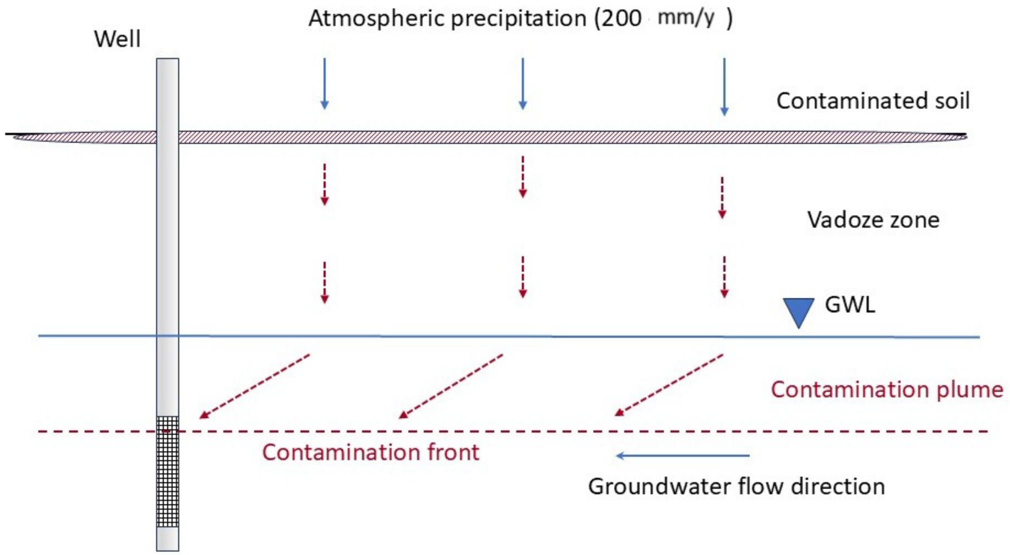
Layout of characterized waste trenches in the central part of the 10-km zone of ChNPP



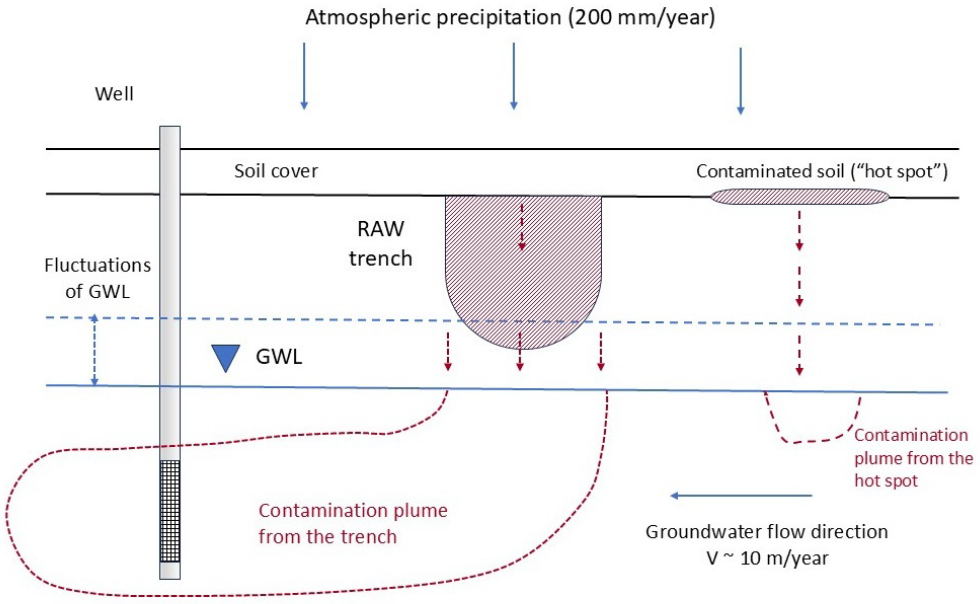
6. Conceptual models for different sources of radioactivity to groundwater

Various sources of groundwater contamination in the Chornobyl zone have resulted in **"stratified" contamination patterns**, with activity levels varying by depth - the upper aquifer strata are typically more contaminated.

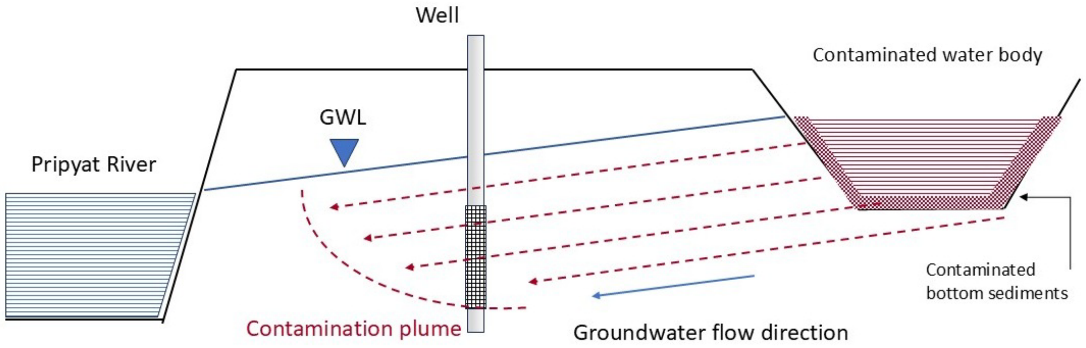
Soils contaminated by radioactive fallout



Waste trenches



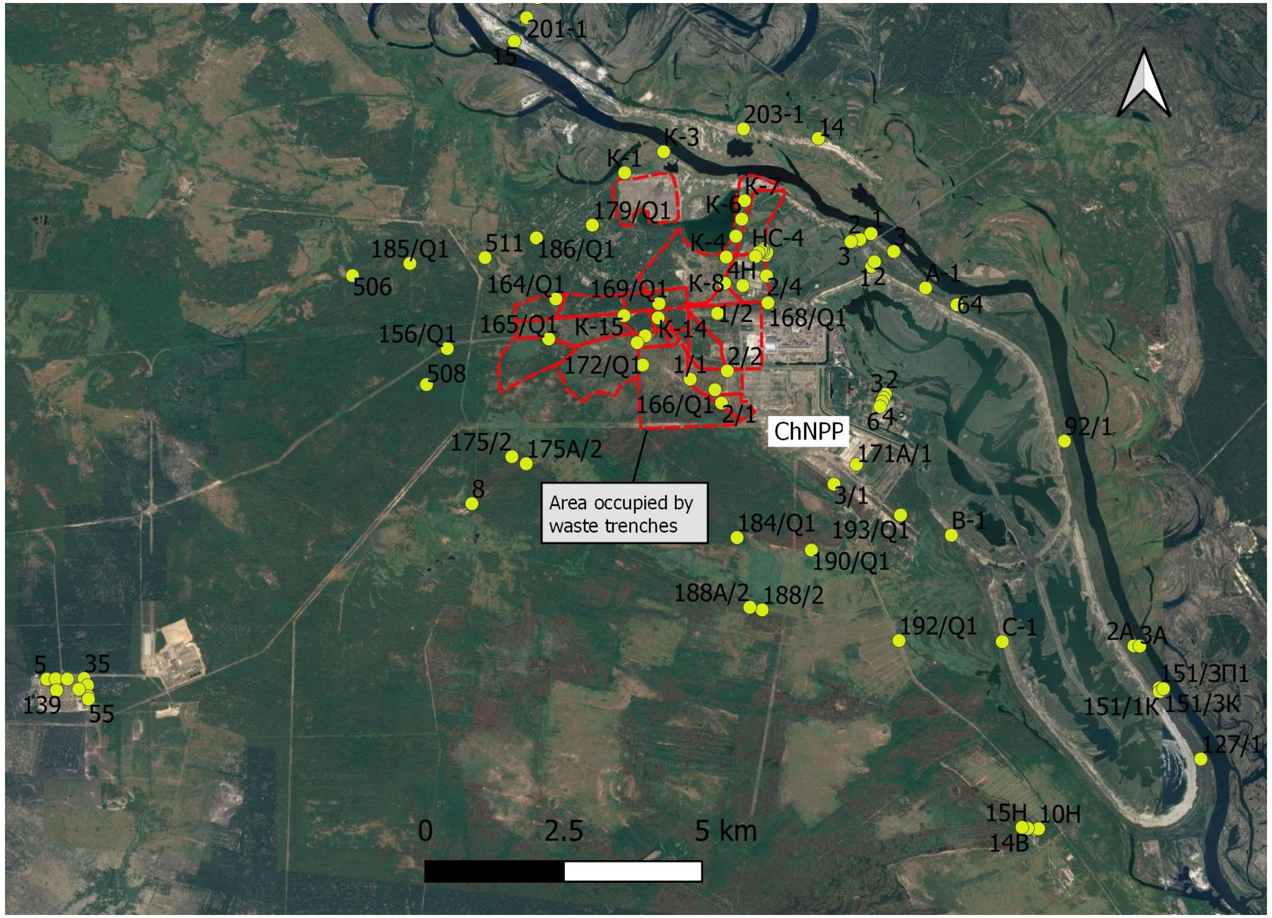
Contaminated water bodies



7. Groundwater monitoring system in the CEZ

- Regional groundwater monitoring in CEZ is conducted by the State Special Enterprise "Ecocenter";
- Monitoring observations have been carried out since 1990;
- Groundwater monitoring network comprises ~150 wells, mostly located in the 10-km zone of the ChNPP;
- Monitored parameters are: ^{90}Sr, ^{137}Cs, $^{239+240}$Pu, and ^{241}Am, groundwater levels;
- Analyses are carried out on unfiltered samples;
- Sampling frequency varies from monthly to quarterly and yearly.

Layout of monitoring wells of the Ecocenter in the 10-km zone of the ChNPP



8. Objectives of groundwater monitoring program in the CEZ

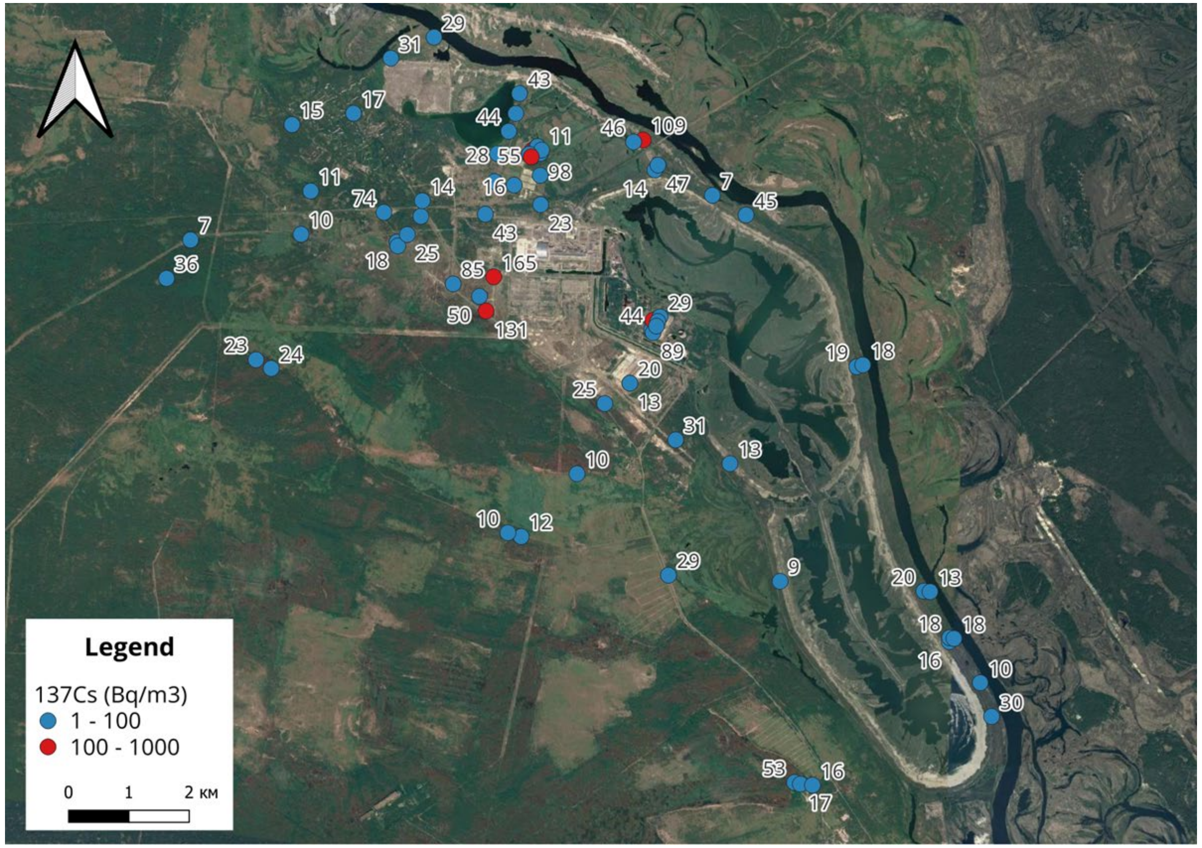
To provide information on groundwater contamination caused by fallout radionuclides of Chornobyl origin and by contaminants released from radioactive waste storage facilities.

Groundwater monitoring data are used for:

- **Fulfilling licensing requirements** for the monitoring of radioactive waste storage and disposal sites;
- Planning and **implementing measures to protect the Pripyat River** and its tributaries from radioactive contamination;
- Providing data to **assess the potential radiological impacts** of contaminated water resources on human health and the environment;
- **Evaluating natural attenuation** of radioactive contaminants in the subsurface environment (to support justification of the Monitored Natural Attenuation [MNA] strategy).

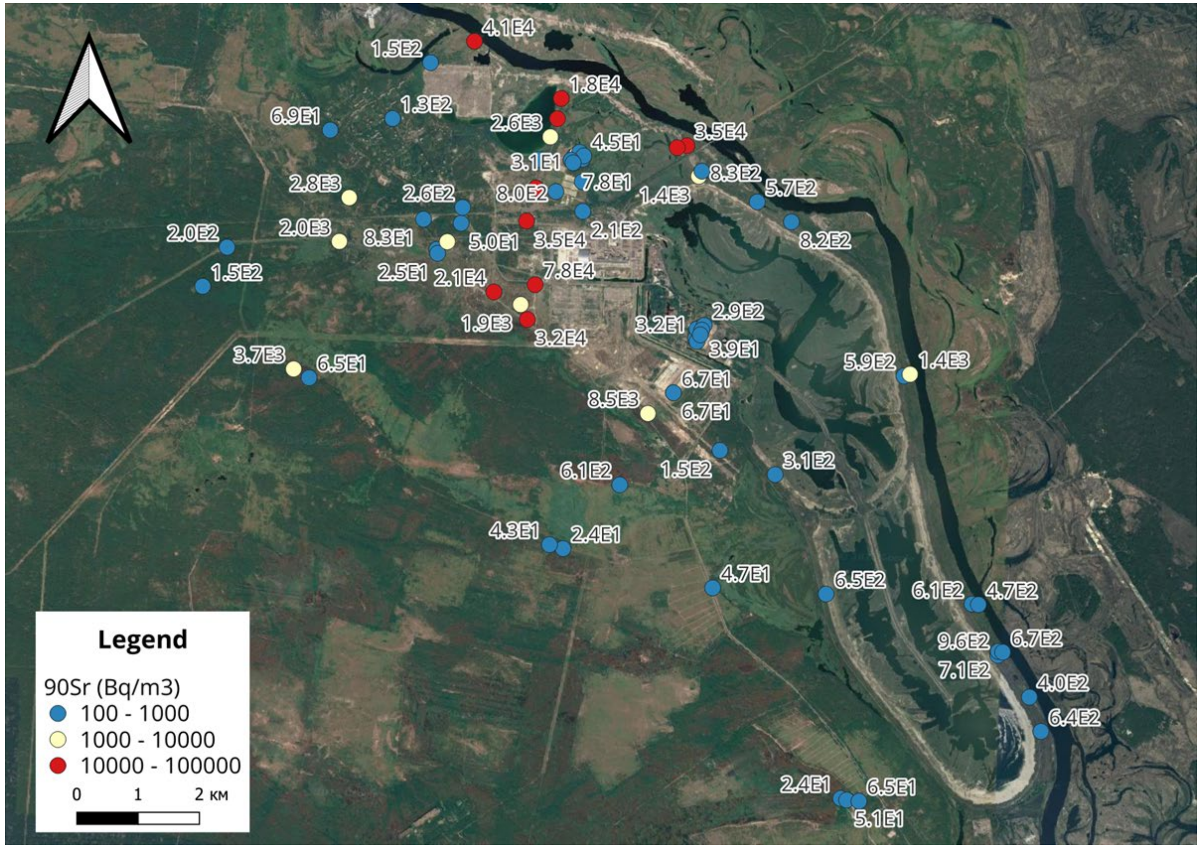
9. Examples of 2D maps of ^{137}Cs and ^{90}Sr in groundwater in 2024 (data of the SSE "Ecocenter")

^{137}Cs



The ^{137}Cs concentrations in the unconfined aquifer vary in the range 10 – 100 Bq m^{-3}, which is below the Ukrainian drinking water standard (DWS) of 2000 Bq m^{-3}

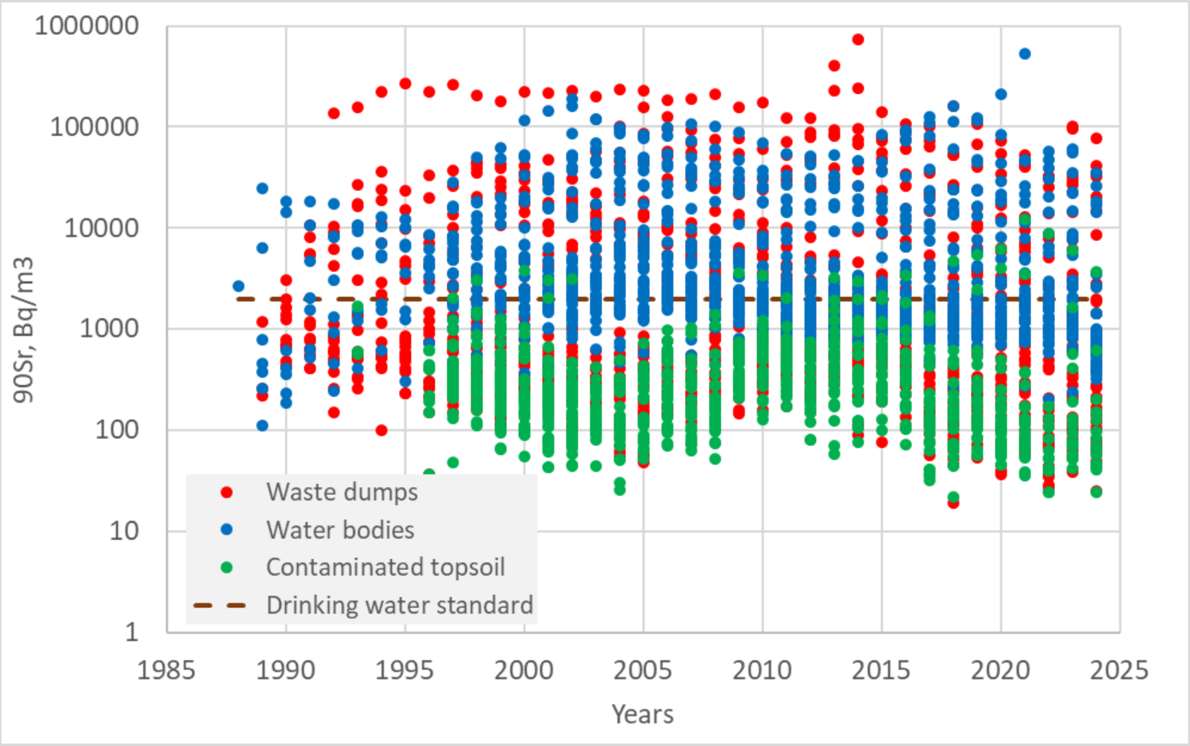
^{90}Sr



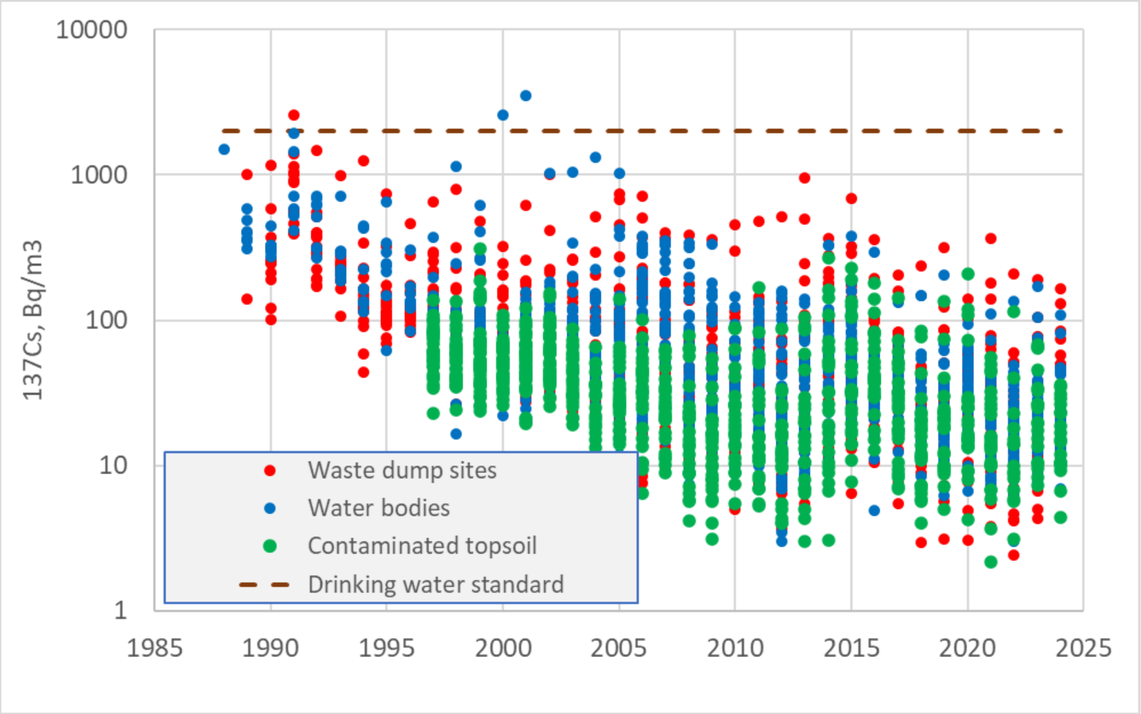
The ^{90}Sr concentrations in groundwater range from 10^2 to 10^5 Bq m^{-3}, and often exceed the Ukrainian DWS of 2000 Bq m^{-3}

10. Time series of radionuclide activity concentrations in groundwater in all monitoring wells

^{90}Sr



^{137}Cs



Time trends of ^{90}Sr are consistent with the CSM assuming the gradual dissolution of nuclear fuel particles and ^{90}Sr downward transport through the vadose zone to groundwater

The observed time trends of relatively low mobile ^{137}Cs are possibly caused by borehole contamination during drilling

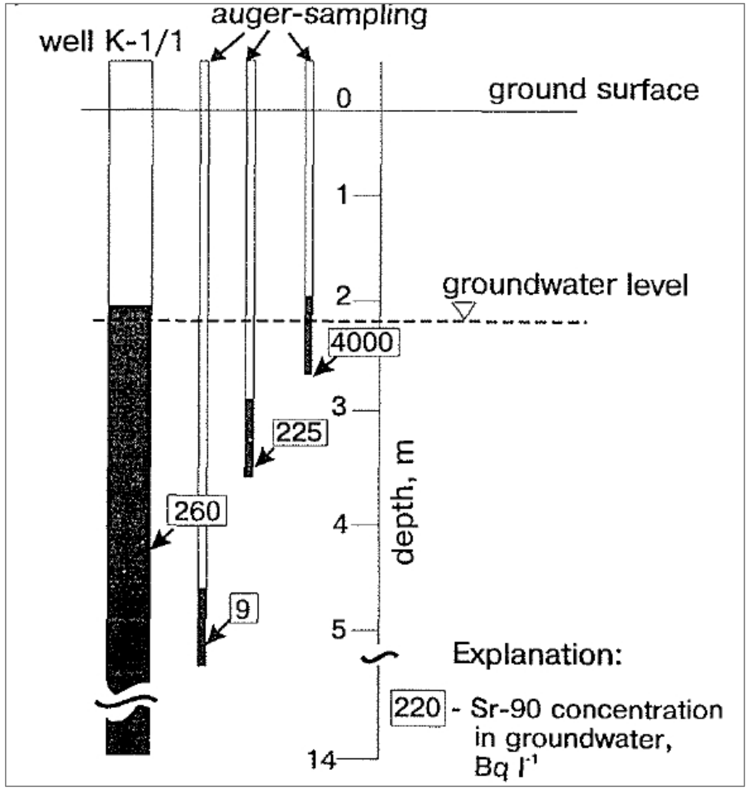
11. Challenges of the existing groundwater monitoring system: Design and placing of wells

The majority of groundwater monitoring wells in the 10-km zone of the ChNPP were installed during 1989–1991 and have a number of shortcomings:

- Wells are constructed with carbon-steel casings (Ø133 mm), which are subject to **corrosion**.
- **Long well screens** (12 m) result in depth-averaged samples and a risk of cross-flow within the well.
- **No sealing of the annular space** was provided, creating the potential for cross-contamination from the surface.
- Wells are irregularly spaced, and their locations often do not adequately account for contamination sources.

The potential radiological impact on downstream receptors, combined with the shortcomings of the existing monitoring system, **underscores the need for modernization** and optimization of groundwater monitoring in the Chernobyl zone.

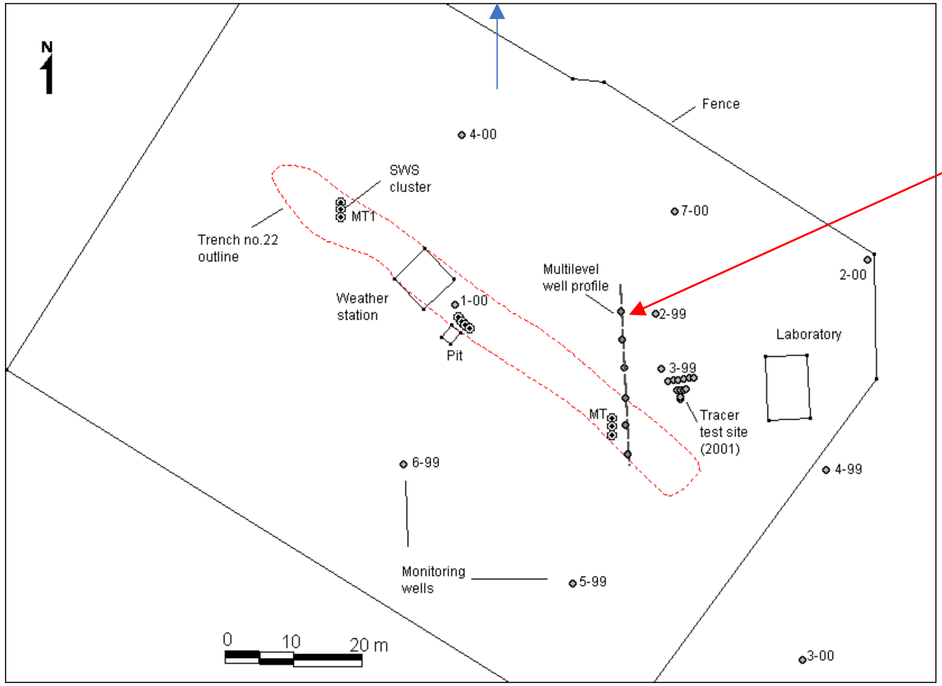
Averaging effect of long screen on ^{90}Sr concentration in groundwater (Dzhepo et al., 1998)



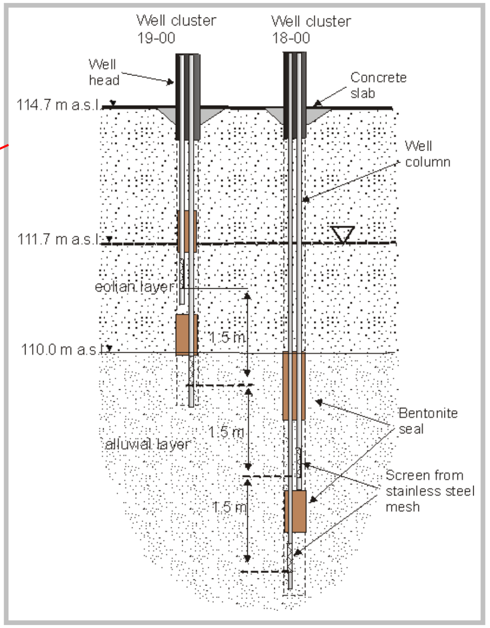
12. Discrete characterization of aquifer contamination: application of 2'' nested multi-level wells to the "Red Forest" waste trench no.22-T

Discrete characterization of aquifer contamination in the vicinity of the waste Trench no.22 at "Red Forest" was carried out in 2000-2012 in the frame of the **Chernobyl Pilot Site/EPIC research projects** funded by the French IRSN (project leaders Lionel Dewiere, Nathalie Van Meir, Caroline Simounucci)

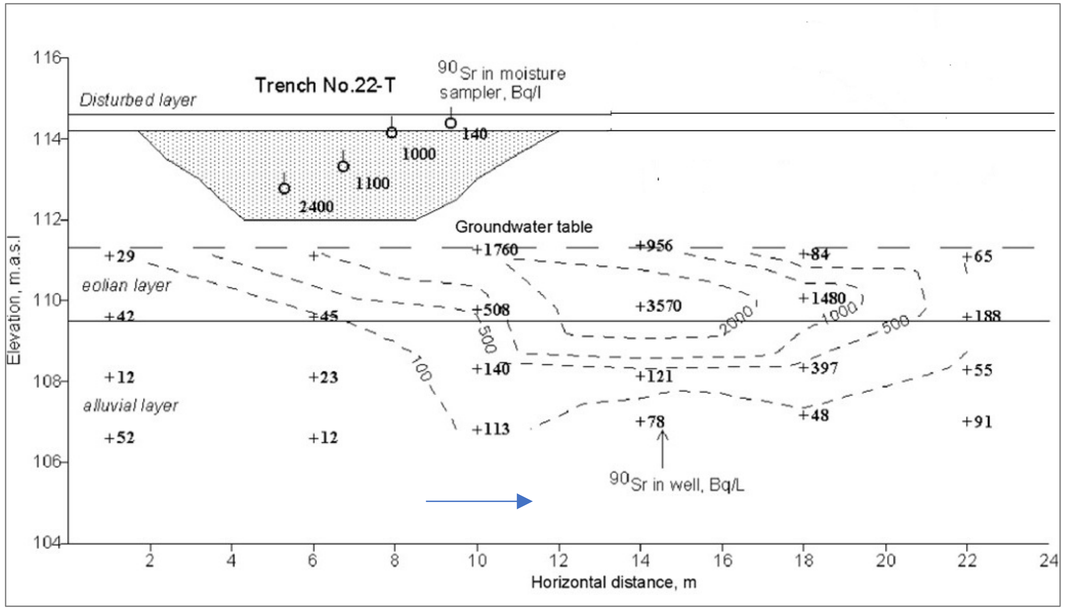
Layout of experimental site near trench 22



Cluster of nested multilevel wells



^{90}Sr distribution in the aquifer cross-section (June 2002)

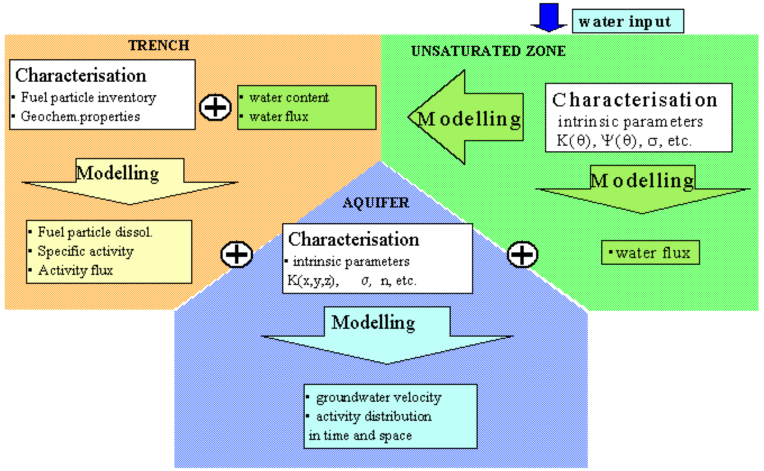


- ^{90}Sr concentrations in groundwater show **migration pattern consistent with leaching from the trench** by infiltration.
- Activity levels in groundwater were 1-2 **orders of magnitude higher** than concentrations measured in Ecocenter monitoring wells.

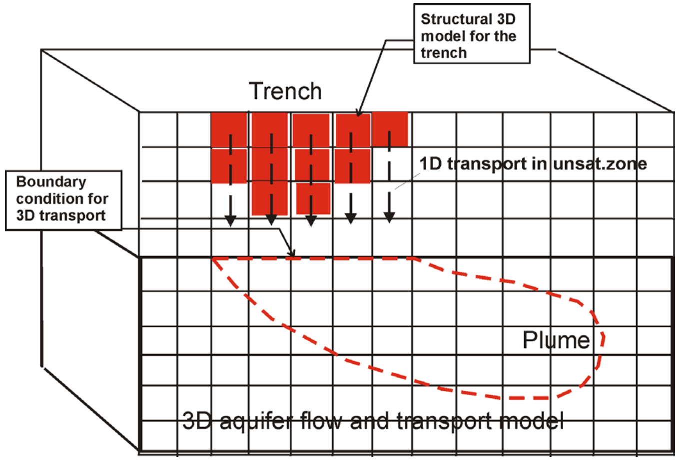
13. The CSM, numerical model and long-term predictions of ^{90}Sr transport in the aquifer

Discrete aquifer characterization data, combined with other field and laboratory studies (tracer tests, lab sorption experiments and dissolution tests of fuel particles, etc.), were used **to develop conceptual and numerical models** for Trench 22.

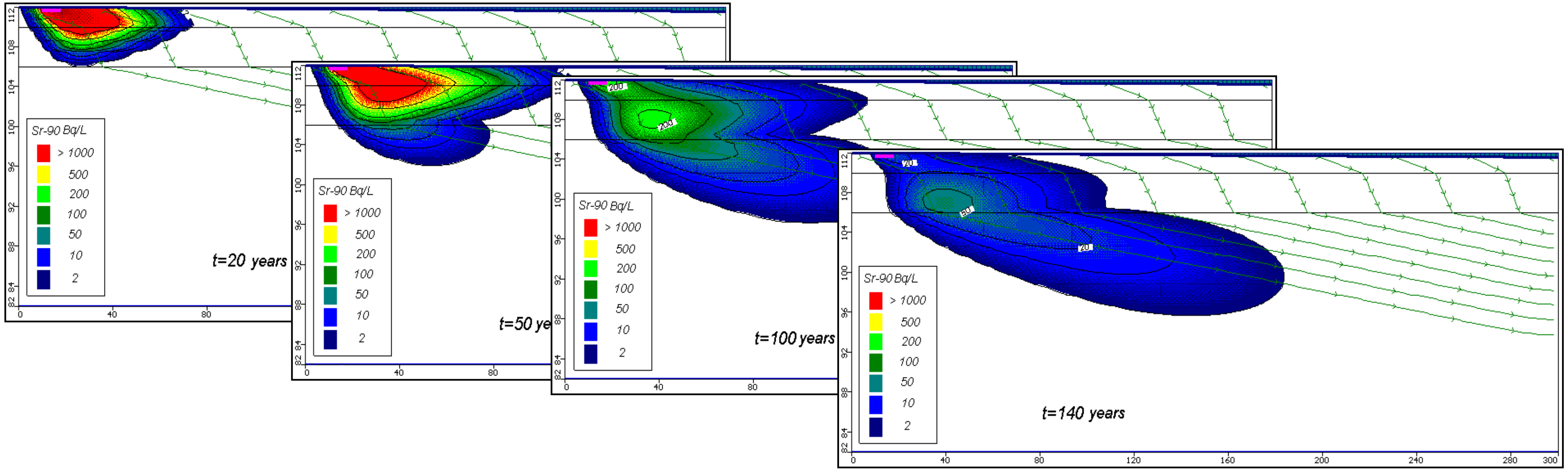
Conceptual Site Model of Trench 22



Scheme of numerical model



Predicted long-term ^{90}Sr transport in the aquifer

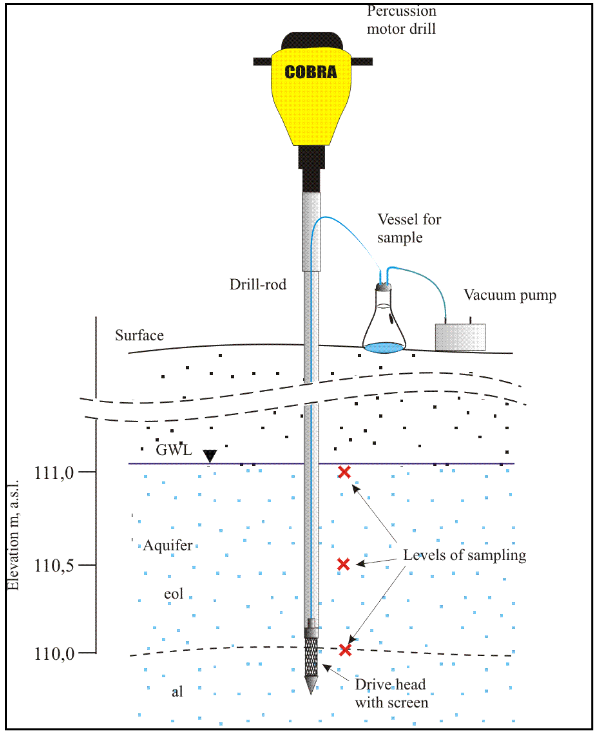


14. Discrete 3D characterization of aquifer contamination: application of the push-auger drill system (Waterloo Profiler)

3D discrete characterization of the aquifer downstream from Trench 22 was carried in October 2002 (to complement data collected using multi-level well profile)

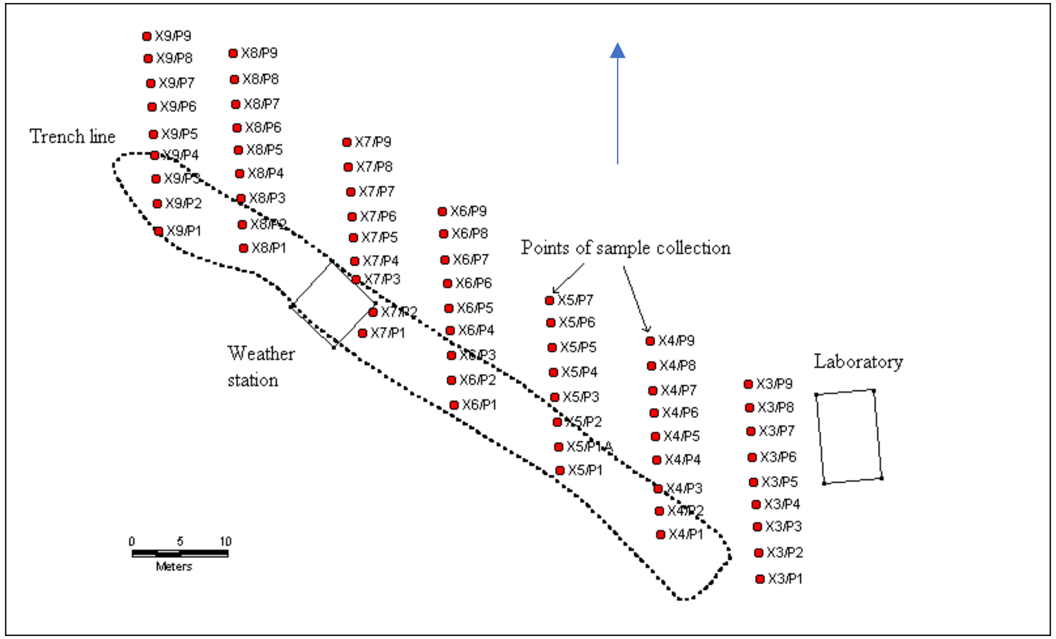
Field sampling using the push-drill system

Push-drill system



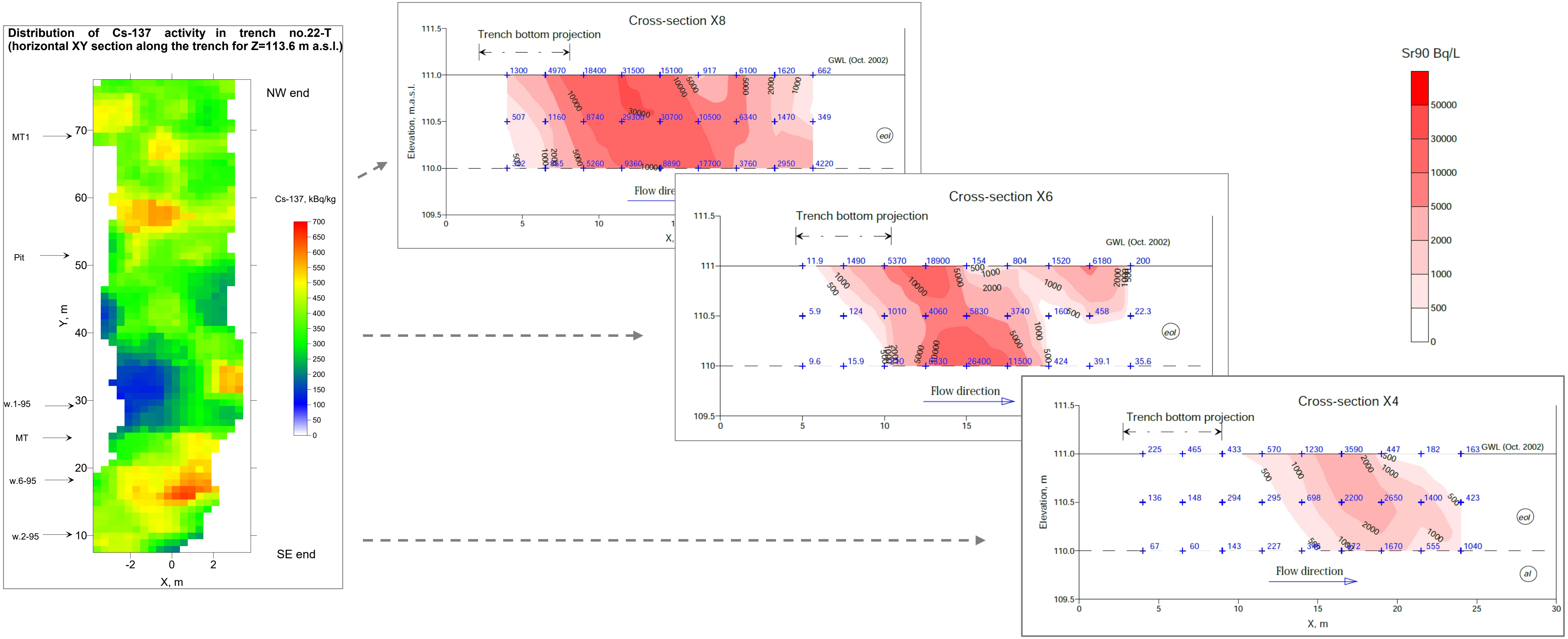
Drive heads with screens

Layout of the push-drill boreholes (drill depth was limited by dense alluvial silt sediment layer)



14. Discrete 3D characterization of aquifer contamination using the push-auger drill system - Results

Discrete characterization revealed **very complex and irregular (spatially, by activity levels) contamination** of the aquifer by ^{90}Sr is 3D which was likely caused by radioactivity heterogeneity in the source of migration - waste Trench 22 and/or preferential infiltration patterns.



16. Approach to modernization and optimization of the regional groundwater monitoring system in the CEZ

Improvement of groundwater monitoring in the Chornobyl Exclusion Zone is supported by the EC INSC technical assistance project #20B to Ukraine (Nov. 2024 – May 2026). The project aims to develop the design for the modernization of the groundwater monitoring system, including the following key sub-tasks:

- **Analysis, modernization, and optimization of the groundwater monitoring networks** using the improved design and placing of wells (key sub-task);
- **Introduction of state-of-the-art and robust groundwater sampling methods** (low flow sampling, control of well purging by monitoring indicator parameters), expansion of the measured parameter list (e.g., addition of basic geochemical indicators), enhancing QA/QC procedures;
- **Implementation of automated monitoring equipment** (e.g., water level loggers);
- Development of an efficient **database - information system for groundwater monitoring data** management and analysis.

17. Addressing challenges in groundwater monitoring

Design of Monitoring Wells

- Replace long-screened wells with **multi-level well clusters** using chemically inert casing (e.g., PVC) and 1–3 m screens to improve vertical resolution and reduce cross-flow.
- Isolate well heads and screened intervals with **bentonite seals** to minimize risk of cross-contamination between aquifer layers.

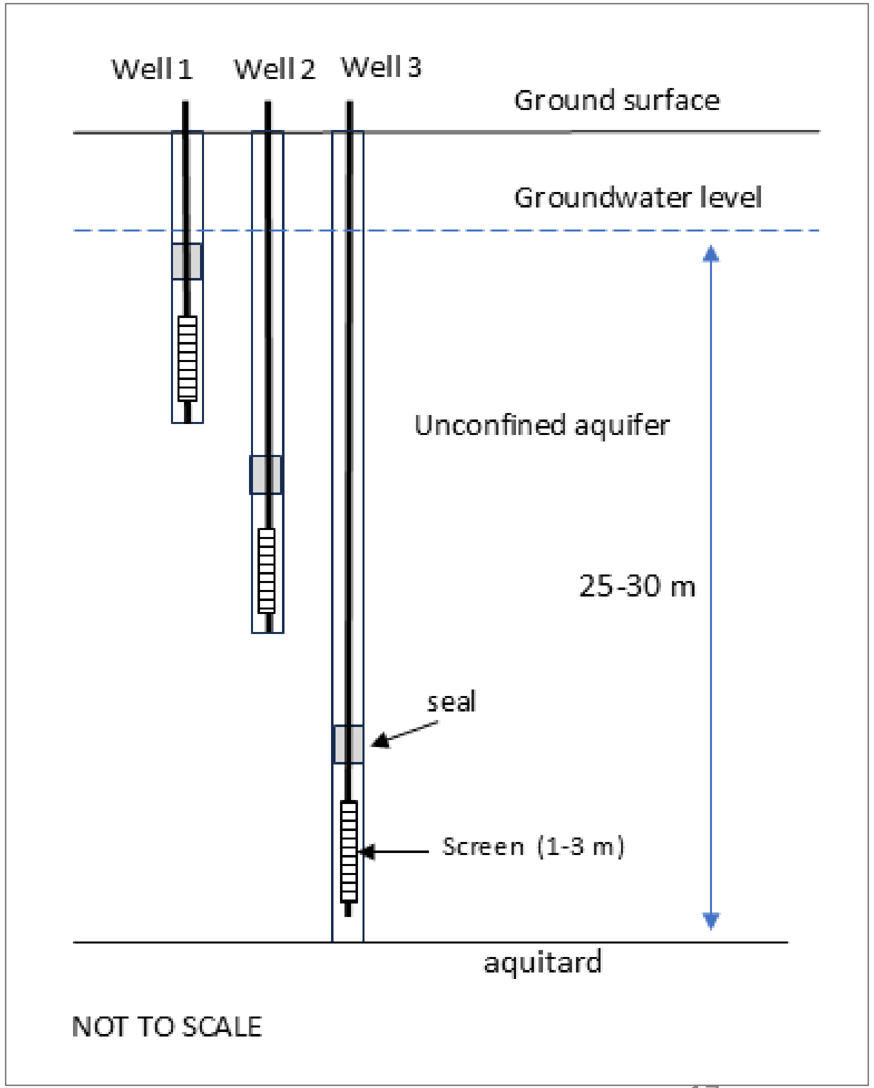
Optimization of Monitoring Network Configuration

- Select well and screen locations considering **target zones** and expected migration distances in the aquifer (based on monitoring data, **discrete characterization studies**, and modelling analyses).

Sampling Schedule

- Adjust sampling frequency to reflect long-term groundwater contamination dynamics (e.g., baseline: biannual to annual).

Design of multilevel monitoring well cluster



18. Conclusions

- Even in relatively simple hydrogeological settings (such as unconsolidated Quaternary sandy formations in the Chernobyl zone), **groundwater flow and radionuclide transport represent spatially complex phenomena**. These are influenced by inhomogeneous source terms, preferential infiltration, and hydraulic as well as geochemical variability of aquifer properties.
- **Discrete aquifer characterization** provides an approach to obtain **consistent monitoring data** that serve as a basis for developing or refining conceptual site models and for calibration/validation of numerical transport models.
- Furthermore, **discrete aquifer characterization can be used to optimize more traditional approaches to groundwater monitoring** (e.g., based on individual wells or multilevel well clusters). This helps to properly configure “standard” monitoring networks—for example, by correctly identifying target aquifer zones, selecting appropriate well screen intervals, and better understanding vertical hydraulic fluxes within the formation.

THANK YOU FOR ATTENTION!