THEORETICAL STUDIES ON LIQUID POLLUTANTS' TRANSPORT IN THE SOIL AND IN THE AQUIFER

MIHAI-COSMIN BELCIU1*, VALENTIN NEDEFF1, ALEXANDRA-DANA CHIŢIMUŞ1, CRISTIAN RADU1

1“Vasile Alecsandri” University of Bacau, Calea Marasesti 157, Bacau, 600115, Romania

Abstract: The present paper describes some theoretical aspects concerning the transport of liquid pollutants in the soil and in the aquifer. The pollution of the geological environment represents the modification of the physical, chemical and biological properties of the soil, altering and restraining the soil's usage properties for its constituent elements (soil, geological formations, phreatic aquifers, deep aquifers). The pollution of the geological environment uses water as its main transport agent, in its entire global circuit: in the atmosphere (vapors and precipitation), at the level of the topographical surface (surface water flowing) and in deep levels of hydrostructures (subterraneous flowing).

Keywords: liquid pollutants, transport, soil, aquifer

1. INTRODUCTION

From an ecological perspective, the soil is one of the most complex ecosystems. Its complexity resides in: its very diverse organic and inorganic composition, the interaction between the various substances and organisms in its composition, its vulnerability to numerous pollutants, or its evolution under the influence of natural and anthropic factors [1-6].

The soil can fulfil the following functions [1, 3, 5, 6]:
- of mechanical support enabling the fixing of plants;
- it is a source of mineral salts, gases and water for plants;
- it participates in the water’s natural circuit and in the circuit of other elements in nature;
- it purifies nature by means of its properties of adsorbing and neutralizing pollutants;
- a deposit and renewable source of fossil energy by means of phytomass transformed in humus.

2. SOIL POLLUTION SOURCES AND FACTORS

Soil pollution is mainly produced in an anthropic manner. In line with industrial and agricultural development, soil pollution takes place as follows [1, 4-7]:
- directly: (generated by internal causes of agricultural activities) by applying chemical fertilizers or pesticides, as well as by applying inadequate techniques and technologies;
- indirectly: by means of emissions of pollutants from industry, transport and other activities, pollutants which come onto contact with the soil and the vegetal layer.

Polluted soils are classified in types, classes and groups (Table. 1) [2, 3].

* Corresponding author, email: dana.chitimus@ub.ro
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Table 1. Classification of polluted soils [2, 3].

<table>
<thead>
<tr>
<th>Classification</th>
<th>Symbol</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class of pollution</td>
<td>PF</td>
<td>physical pollution</td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>chemical pollution</td>
</tr>
<tr>
<td></td>
<td>PB</td>
<td>biological pollution</td>
</tr>
<tr>
<td></td>
<td>PR</td>
<td>radioactive pollution</td>
</tr>
<tr>
<td>Types of pollution</td>
<td>Pa</td>
<td>pollution by excavating</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>cover pollution by waste dumps, tailings, waste</td>
</tr>
<tr>
<td></td>
<td>Pc</td>
<td>waste and inorganic waste pollution</td>
</tr>
<tr>
<td></td>
<td>Pd</td>
<td>pollution by substances carried by the wind</td>
</tr>
<tr>
<td></td>
<td>Pe</td>
<td>radioactive material pollution</td>
</tr>
<tr>
<td></td>
<td>Pf</td>
<td>organic waste pollution in food industries</td>
</tr>
<tr>
<td></td>
<td>Pg</td>
<td>forestry and agricultural waste pollution</td>
</tr>
<tr>
<td></td>
<td>Ph</td>
<td>animal waste pollution</td>
</tr>
<tr>
<td></td>
<td>Pi</td>
<td>human waste pollution</td>
</tr>
<tr>
<td></td>
<td>Pj</td>
<td>pollution through erosion and sliding</td>
</tr>
<tr>
<td></td>
<td>Pk</td>
<td>pollution by salting</td>
</tr>
<tr>
<td></td>
<td>Pl</td>
<td>pollution through acidification</td>
</tr>
<tr>
<td></td>
<td>Pm</td>
<td>pollution by excess water</td>
</tr>
<tr>
<td></td>
<td>Pn</td>
<td>pollution by excess (deficiency) of nutrients</td>
</tr>
<tr>
<td></td>
<td>Po</td>
<td>pollution by compaction, crusting</td>
</tr>
<tr>
<td></td>
<td>Pp</td>
<td>pollution by sediment cover</td>
</tr>
<tr>
<td></td>
<td>Pq</td>
<td>pesticide pollution</td>
</tr>
<tr>
<td></td>
<td>Px</td>
<td>pathogen pollution contaminants</td>
</tr>
<tr>
<td>Degree of pollution</td>
<td>0</td>
<td>practically unpolluted (reducing production below 5%)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>low pollution (6-10% reduction)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>average pollution (11-25 % reduction)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>highly polluted (26-50 % reduction)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>very highly polluted (51-75 % reduction)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>excessive pollution (reduction 75 %)</td>
</tr>
</tbody>
</table>

Figure 1 presents the main sources of soil pollution [1- 6].

Fig. 1. The main sources of soil pollution [1- 6].
3. LIQUID POLLUTANTS' TRANSPORT IN THE SOIL AND IN THE AQUIFER

By discharging a liquid pollutant on the soil surface an impregnation area is generally created due to phenomena such as convection, dispersion, adsorption, precipitation and biological activity [8-12]. The direction and speed of the pollutant’s movement depend on its viscosity, on the ground’s morphology and on the permeability of the soil and of the rocks from the aquifer. The major force which acts on the pollutant is gravitation. As a result, if the soil is permeable, the pollutant permeates the soil vertically, while a lateral impregnation also occurs due to dispersion resulting from soil porosity. In its migration to the aquifer, the pollutant can be filtered, adsorbed (Figure 2), volatilized, precipitated, biodegraded and, to a smaller extent, hydrolyzed, oxidized and reduced. Similarly, it can be blocked by an impermeable barrier [13-16].

![Fig. 2. Migration of pollutants in soil and aquifer [13-16].](image)

The physical, geophysical, biophysical and biological processes taking place in soils (Figure 3) which undergo pollution processes most commonly lead to the retention of the pollutant and its partial or total transformation, the negative effects of pollution being thus diminished to a great extent [2, 3, 6, 17].

![Fig. 3. Processes controlling the behavior of pollutants in the soil and in the aquifer [2, 3, 6, 17].](image)

The structure/frame of the subterranean environment is made up of minerals and rocks of different granulometric sizes, the interconnection of their pores enabling the circulation of water [4, 8-10, 13, 18].
If we analyze the soil downward from its surface towards its depth we may distinguish (Figure 4) [4, 8-11, 13, 18] the following zones:

- **The unsaturated zone**: pores are partially filled/saturated with water and also partially filled with air, a fact which allows the coexistence of the solid, liquid and gaseous phases. The soil is located in the upper layer of the unsaturated zone where biological processes take place.

- **The saturated zone**: pores are completely filled/saturated with water, and the flow of liquids in this area takes place in response to the flow of subterranean waters.

The saturated zone or aquifer is made up of two distinct phases: a solid immobile phase (made of rocks) and a liquid mobile phase, namely the subterraneous water/groundwater [4, 8, 9, 18].

The separation between the two phases is made by the hydrostatic level. Above the hydrostatic table/water table the capillary fringe or zone is located, in which water fills pores by capillary action [10, 11, 13, 16].

3.1. Liquid pollutants’ transport in the unsaturated zone of the soil

The main factors taken into consideration for estimating the migration of pollutants in the unsaturated zone are [4, 8-11, 13, 19-21]:

- for the soil:
  * texture;
  * structure;
  * porosity;
  * permeability;

- for pollutants:
  * viscosity;
  * solubility;
  * volatility.

The measures which characterize the migration of pollutants in the unsaturated area are: maximum penetration depth of the pollutant in the unsaturated area, the volume of pollutants retained in the unsaturated area, and transfer time of the pollutant in the unsaturated area [22-30].

**The maximum penetration depth of the pollutant in the unsaturated area** (Figure 5) can be calculated using formula (1) [11-14, 17, 26, 27].

\[
H = K \cdot \frac{V}{A} [m]
\]
in which: $H$ is the maximum penetration depth of the pollutant in the unsaturated area (m); $V_i$ - volume of infiltrated pollutants ($m^3$); $A$ - the infiltration zone surface ($m^2$); $K$ - stands for dimensionless coefficient.

![Diagram of pollutant transport](image)

**Fig. 5. Liquid pollutants’ transport in the unsaturated zone of the soil [11-14, 17, 26, 27].**

In order to calculate the dimensionless coefficient, the following relation can be employed [11, 13, 27, 30]:

$$K = \frac{1000}{R \cdot k} \quad (2)$$

in which: $R$ is the pollutant retention capacity of the soil ($L/m^2$); $k$ –the dimensionless correction coefficient/factor depending on the pollutants’ viscosity.

Table 2 presents a number of values for $R$ and $k$ corresponding to different soil textures [11, 13, 29, 30].

<table>
<thead>
<tr>
<th>Type of pollutant</th>
<th>The coefficient $k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halogenated solvents</td>
<td>0.3</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.5</td>
</tr>
<tr>
<td>Aqueous solution</td>
<td>0.7</td>
</tr>
<tr>
<td>Diesel, kerosene</td>
<td>1</td>
</tr>
<tr>
<td>Fuel slightly</td>
<td>2</td>
</tr>
</tbody>
</table>

**Table 2. Values of coefficient $k$ depending on pollutant type [11, 13, 29, 30].**

The volume of pollutants retained by the unsaturated zone is calculated by means of relation (3) [14, 16, 22-24, 26].

$$V_r = \frac{A \cdot h \cdot R \cdot k}{1000} \quad [m^3] \quad (3)$$

in which: $V_r$ is the volume of pollutants retained by the unsaturated zone ($m^3$); $h$ - the thickness of the unsaturated area (m).
The transfer time of the pollutant in the unsaturated area can be estimated starting from the experimental value of permeability for water corresponding to the type of soil and to the characteristics of the unsaturated zone. The permeability value for the pollutant in the unsaturated zone is calculated using formula (4) [14, 16-18, 22-24, 26].

\[ K_p = K_a \cdot \frac{v_a}{v_p} \ [m/s] \]  

in which: \( K_p \) represents the permeability of the unsaturated zone for the pollutant (m/s); \( K_a \) - permeability of the unsaturated zone for water (m/s); \( v_a \) – the kinematic viscosity of water; \( v_p \) – kinematic viscosity of the pollutant.

The average transfer time can be approximated by using formula (5) [17, 18, 22-24, 26].

\[ t = \frac{V_p}{Q_p} = \frac{A \cdot h \cdot w}{K_p \cdot w} \ [s] \]  

in which: \( t \) is the average transfer time (s); \( V_p \) - water volume in the impregnation area (polluted area) (m³); \( Q_p \) – the pollutant’s infiltration debit (m³/s); \( W \) – signifies the humidity of the unsaturated area, (%/100); \( h \) - thickness of the unsaturated area (m).

3.2. Liquid pollutants’ transport in the saturated zone of the soil

By crossing the unsaturated zone of the soil, a part of the pollutants’ volume is retained by the soil and by the rocks from the top-layer of the aquifer. Pollutants which reach the saturated area (aquifer) behave differently, depending on their physical, chemical and biological properties [4, 8-11, 13, 23].

The main phenomena that characterize the transport of pollutants in the aquifer are advection, diffusion, dispersion and retardation factor [11, 23-25].

**Advection** represents the transfer of blendable/miscible pollutants in the subterranean water as a result of its flow. One of the most important elements of convection transfer is the subterranean water flow speed [9-11, 23].

**Diffusion** is the transport process of a substance and is determined by the concentration gradient occurring between the various points of the aqueous solution of that substance. Diffusion also takes place when the support fluid, respectively water, is in static conditions. In less permeable subterranean mediums, the transport of pollutants by means of diffusion processes is more important from a quantitative viewpoint as compared to advection transport [4, 8 - 10, 24, 25, 30].

**Dispersion** is the phenomenon showing the blending of the pollutant with water, leading to decreasing levels in the pollutant’s concentration in the subterranean water. The dispersion of pollutants takes place as follows: by means of mechanical phenomena such as the winding flow of the fluid through the pores of aquiferous rocks, the rubbing of the fluid against the particles of aquiferous rocks and the differences in horizontal permeability in the aquifer. Such a type of dispersion is also known as mechanical dispersion. Dispersion takes place both in accordance with flow direction/along the flow (longitudinal dispersion) and perpendicular to the aquifer flow direction (transverse dispersion). Figure 6 presents a diagram of the liquid pollutants’ dispersion in the soil as a result of changes (at microscopic levels) of flow directions [9, 10, 17, 18, 24, 25].

**The retardation factor** encompasses those phenomena which lead to restraining the migration of pollutants in the aquifer, such as [8, 11, 13, 17, 18, 23-25]:

- adsorption, by means of which polluting molecules or ions in aqueous solution are attracted by electrical or chemical forces towards the surface of granules which make up aquiferous rocks;
- pollutant precipitation or complexation in case of pollutants in aqueous solution, and the formation of insoluble compounds (metallic hydroxides or carbonates, organometallic complexes etc.);
- degradation of organic compounds as a result of the biological activity in the soil;
- volatilization.
3.3. Migration of water soluble pollutants in the soil

Water soluble pollutants follow the track of infiltration waters both in unsaturated and saturated zones [1, 3, 7, 14, 15].

The quantity of pollutant retained by the unsaturated area is determined by the quantity of water in the soil and in rocks, by their physical, chemical and biological properties, as well as by the salt concentration of the soil solution [2, 16-18, 22].

When the pollutant in aqueous solution reaches the saturated zone, it undergoes the dispersion process, forming a pollution area which is parallel to the flow direction of subterraneous water [22, 27, 28, 30].

3.3.1. Migration in the soil of immiscible pollutants which are even lighter than water

This situation occurs in case of polluting the subterraneous environment with hydrocarbons (gas, oil, Diesel oil, or other liquid fuels). In the unsaturated zone, the pollutant forms an impregnation area from which certain fractions can be directed towards the atmosphere in the form of vapors, or towards the aquifer by means of progressive solubilization determined by infiltration waters [4, 8, 10-13, 22, 23].

When touching the aquifer, the pollutant stretches progressively forming a floating net/layer at the interface between the unsaturated and saturated zones (Figure 7). The creation of this net depends on the flow speed of the subterraneous water, and chiefly on the properties of the rocks situated at the interface between the two zones (particularly the capacity of these rocks to retain the pollutant or to support its passage) [11, 12, 22-25, 30].

When touching the upper level of the aquifer, a part of the pollutant will continuously move in the flow direction of the subterraneous water, and another part will be immobilized in capillary fringes [22, 24, 25, 29, 30].

If the pollutant is a complex hydrocarbon (for instance, a type of power fuel), at the interface between the water and the pollutant specific solubilization phenomena occur. The most soluble parts of the hydrocarbon (benzene, toluene, xylene) dissolve progressively in water, modifying the initial contents of the pollutant. A differentiation exists concerning the proportion of soluble fractions and little soluble aliphatic fractions of the pure pollutant and of the fraction dissolved in water [1, 3, 7, 22, 23, 29, 30].

Floating hydrocarbons can often be dispersed in the subterraneous water in the form of fine emulsions or can be volatilized, thus giving birth to explosive vapors which are diffused in the unsaturated zone [8, 9, 22-24, 27].

3.3.2. Migration in the soil of immiscible pollutants which are even heavier than water

This is the case of halogenated solvents. The impregnation area formed by halogenated solvents in the unsaturated zone is less extensive than in the case of oil products [4, 8-10, 13, 14].

From the impregnation area the pollutant can be solubilized progressively and directed towards the aquifer with the support of meteoric waters. An important quantity from the liquid polluting product can switch to its vapor phase and then it spreads around the impregnation area [10, 12-14, 16].
After reaching the aquifer, the liquid pollutant will tend to settle at the bottom layer of the aquifer as a result of the fact that its density is higher than that of water (Figure 8). The movement of the pollutant in the aquifer depends on the flowing conditions of the subterranean water (the gradient and the shape of the impermeable substratum, the speed and flow direction of subterranean waters) [12, 16, 17, 22-24, 27, 30].

4. CONCLUSIONS

Soil decontamination must be carried out having in view the close relationship between the soil and subterranean waters, which are basic components of the environment. Currently, soil decontamination methods in the international context target the system comprising the soil and the subterranean water.
Pollution propagation vectors, transfer or migration vectors, the migration, transport and dispersion route of pollutants can be of various forms, depending on transfer media: water, air, soil.

The migration of immiscible pollutants in the soil depends on their density; those with lower density than water tend to rise to the surface and to settle in the upper part of the aquifer. Higher density pollutants tend to go downward in relation to the water flow direction and generally deposit in the impermeable area of the aquifer.

The dispersion of the pollutant in various environments/media is determined by:
- characteristics of the environment, which allow the evaluation of its vulnerability, respectively the possibilities concerning the pollutants’ penetration and migration. In case of vertical migration, the most important parameters are: the nature of the soil/soil type, texture, porosity, compactness, depth at which the aquifer is located, the presence of subterranean constructions. The migration of pollutants in subterranean waters is conditioned by the flow speed of subterranean waters, granulometric determination, permeability of aquiferous rocks, the existence of natural or artificial obstacles etc.
- processes contributing to the migration of pollutants in the environment (convection, dispersion, diffusion, adsorption).

REFERENCES


