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CONCEPTS OF A SURVIVAL AND TRANSPORT MODEL OF PATHOGENIC BACTERIA AND VIRUSES IN GROUNDWATER

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ABSTRACT

For the assessment of the transport of bacteria and viruses in groundwater and for the interpretation of the available data, certain controlling factors should be determined. The survival time of bacteria and viruses in groundwater is different for the specific species and for the specific groundwater environment (temperature, groundwater chemistry and autochthonic population of microorganisms). The survival time depends on the specific elimination rate in a certain environment and on the initial concentration of the pollutants. The underground transport of the microorganisms which may be described by the general transport equation, must consider dispersion, adsorption and biological elimination. Since there is a wide range of variation in the available data, model calculations of the transport are necessary. Furthermore the effects of filtration and suffosion are considered to be of importance.

INTRODUCTION

For the assessment of groundwater protection zones against pathogenic microorganisms (bacteria and viruses), the mechanisms which control the two main factors for their elimination in the aquifer must be studied:

i) the persistence of bacteria and viruses under the biological and chemical conditions of the groundwater

ii) the physical and physico-chemical processes which control the transport of microorganisms in groundwater.

The most important pathogenic bacteria and viruses which might possibly be transported on the water path are: Salmonella sp., Shigella sp., Vibrio cholera, Yersinia enterocolitica, Y.pseudo-

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~~tubercu~~tuberculosis, Leptospira sp., Francisella tularensis, Dyspepsia coli, enterotoxine forming E.coli, Pseudomonades and the viruses, the agents responsible for infectious hepatitis, polio viruses, coxsackie viruses and ECHO viruses. The groundwater may be contaminated by sewage containing the excrement of carriers or diseased persons. In municipal sewage, the concentration of E.coli is in the order of 10^5-10^6/ml and in surface waters about 10^2-10^3/ml. In Central European rivers usually 1-3 Salmonella/l are detected.

The virus concentrations in the USA are as high as 10^2-10^4 PFU/l in sewage effluent, 10^0-10^3/l in treated sewage effluent and 0-10^2/l in surface waters. According to EPA (Ref.1) drinking water which has undergone conventional treatment would contain about 1 infectious unit in 10^5-10^8 l. This means the virus concentration in the waste water has to be eliminated by 7 log units before the water is usuable as drinking water. About the same order of magnitude holds for the necessary elimination of bacteria: sewage effluent contains about 10^6 E.coli/100 ml, drinking water should contain no E.coli in 100 ml. The same approach may be used for groundwater.

SURVIVAL OF BACTERIA AND VIRUSES IN GROUNDWATER

Two groups of microorganisms are to be differentiated when the survival of bacteria and viruses in groundwater are considered:

i) allochthonic pathogenic microorganisms (parasitic bacteria and enterotoxine producing bacteria) which enter the groundwater due to contamination

ii) autochthonic groundwater microorganisms.

The autochthonic microbial groundwater population flourishes under favourable ecological conditions, developing high population densities ($\gg 10^3$/ml). The allochthonic bacteria are usually eliminated in the groundwater environment, but under oligotrophic conditions they may survive without a substantial decrease or even slight increase in the germ number during the first 1 - 7 days. After this period, the elimination of bacteria and viruses may be approximately described by an exponential function (Ref.2):

$$C_{(t)} = C_0 \, e^{-\lambda(t-t_0)} \qquad (1)$$

$t \geq t_0$ and $t_0 \leq 7$ days

$C_{(t)}$ = concentration at time t

C_0 = initial concentration

λ = elimination rate

t = time

The equation holds also for viruses (Ref. 3). Equation (1) allows one to estimate the order of magnitude of the number of bacteria and viruses at any time, depending on the initial contamination. Furthermore, it follows from equation (1) that after a very rapid elimination at the beginning (the halflife of most bacteria and viruses d_{50} ranges between 1 - 20 days) it will decrease so that even after longer times, bacteria and viruses may still exist in very small quantities in groundwater.

The elimination rate depends on physical, chemical and biological parameters and is specific for the different microbial species (Ref. 4). It is not yet possible to predict with the necessary accuracy the elimination rate on the basis of controlling factors. Therefore the elimination rate must be measured for each specific species and environment. The published values vary over a broad range, e.g. for a 99,9 % elimination of Salmonella typhi time intervals between 2 and 107 days are quoted. Besides the varying parameters mentioned above, different experimental methods lead to deviations in the results. For example Salmonella typhimurium is found in laboratory measurements (Ref.2) to be more resistant in the groundwater environment than S.typhi or E.coli (230 days, 8 and 23 days respectively). In situ experiments with membrane filter chambers in groundwater gave contradictory results (Ref. 5). The most important ecological factors are the physical (temperature), biological and chemical conditions. These have a combined effect due to interaction and complementary impacts. The biological factors (concentration of autochthonous bacteria, bacteriophages etc.) are presumably the most important factors for the survival of pathogenic bacteria and viruses, although these depend extensively on the physico-chemical properties of groundwater. In sterilized water or in water with low biological activity, the viruses and bacteria survive longer than in the presence of higher contents of organic compounds or at favourable pH-values (about pH 7) and with low oxygen concentrations. In contaminated water or in surface water with high biological activity, the elimination rate is higher under the same physical and chemical conditions due to the activation of the autochthonous bacteria which can compete very effectively with the pathogenic bacteria. Bacteriophages and parasitic bacteria (e.g. Bdellovibrio bacteriovorus and protolytic bacteria) when present in higher concentrations, accelerate the elimination. The endospore building bacteria are less affected by the biological factors than the bacteria.

Unter favourable conditions, at temperatures up to 15 °C pathogenic bacteria and viruses can survive for a long period:
E.coli $>$ 100 d, Salmonella typhi $>$ 100 d, Salmonella typhimurium $\leq$ 230 d, other Salmonellae $\leq$ 70 d, Yersinia sp. $\leq$ 200 d, Poliovirus $\geq$ 250 d.

The published data on the elimination of bacteria and viruses in aquifers show that the survival time cannot be the only criterion for the purifying effect of underground passage. Therefore the physico-chemical transport processes are to be considered.

TRANSPORT PROCESSES

In porous aquifers (e.g. sand and gravel) the main transport takes place in the pores. The groundwater velocities are usually less than one meter/day up to a few meters/day, velocities above 10 m/day are rare. In hard rock aquifers, the groundwater flow velocities in fissures are quoted to be between 0.3 m and 8000 m/day, in karstic aquifers up to 26.000 m/day. Therefore it can be concluded that the propagation of pollutants in fissured and karstic aquifers is much faster than in porous aquifers. Furthermore the larger diameters of the flow paths in fissures and solution canals of hard rocks should allow a better transport of suspended microorganisms. Groundwater velocity may be calculated from hydraulic conductivity, hydraulic gradient and porosity as a mean velocity, or measured by tracer experiments from which the mean velocity and a maximum velocity (from first arrival of measurable tracer amounts at the observation point) can be derived. The maximum velocity is important for the assessment of the vulnerability of groundwater works to pathogenic microorganisms, indicating the possiblility of the first arrival of microbial pollutants.

Microorganisms are subject to adsorption on underground particles. This may be described for diluted suspensions by the FREUNDLICH' isotherm (Ref. 2) which defines the equilibrium between the concentration of the suspended (C_s) and adsorbed (C_a) microorganisms (2).

$$C_a = kC_s^n \qquad (2)$$

Where k and n are assumed to be specific constants for the investigated rock and microorganisms. The FREUNDLICH' isotherm shows that the adsorption of microorganisms can be reversible. The adsorption of viruses and bacteria takes place quite rapidly (2h and 24h respectively). Desorption velocity is not as well known as the adsorption velocity and should be measured in further investigations. Another possible description may be the LANGMUIR' isotherm (3) which possibly is the better mathematical definition of the nature of the adsorption processes

$$C = \frac{K \cdot b \cdot C_s}{1 + K \cdot C_s} \qquad (3)$$

where K is a constant relating to the bonding energy and b the adsorption maximum when the adsorbent is completely saturated. The continous adsorption - desorption reactions cause a retardation of the microorganisms with respect to the surrounding groundwater. Due to this retardation, more time for the elimination of bacteria and viruses is available. The retardation of the microorganisms is described by the retardation factor R_d, the quotient of water velocity V_w to the velocity of microorganisms V_m (4). The retardation factor can be calculated if the distribution coefficient K_d of bacteria and viruses is known (4)

$$R_d = \frac{V_w}{V_m} = 1 + \frac{\rho_b}{n} \cdot K_d \qquad (4)$$

with the bulk density of the aquifer material ρ_b, its porosity n, the mean groundwater velocity V_w and the mean transport velocity of the microorganisms V_m. The empirical distribution coefficient K_d (ml/g) can be obtained by batch tests in the laboratory. It defines the affinity of the aquifer material for a certain contaminant. K_d is in diluted suspensions equal to the coefficient of the FREUNDLICH' or LANGMUIR' isotherm. If the average velocity of the groundwater V_w, of the contaminant V_m, ρ_b and n are known, the actual K_d-values can be calculated by laboratory and field experiments. In field experiments, retardation factors between 1 and 2 are found for bacteria (E.coli and Serratia marcescens). The viruses in general, especially the polio viruses, have very high K_d-values, depending on water properties and the properties of the respective virus. Due to eq (4), retardation factors of up to 500 can be expected in loamy aquifers with higher cation concentrations. Models using the data of the known adsorption coefficients and elimination rates, show that the underground passage can provide a very effective protection against virus contamination. However according to other observations the viruses can be desorbed again, when cation concentrations decrease (for example by a very intensive rainfall), thus being enabled to travel further (Ref. 6). Model calculations using data of GERBA & GOYAL (Ref. 7) for virus adsorption and elimination rate of viruses from AKIN (Ref. 8) show that the transport of viruses can be very different depending on the water chemistry, for the same elimination rate (Fig. 1).

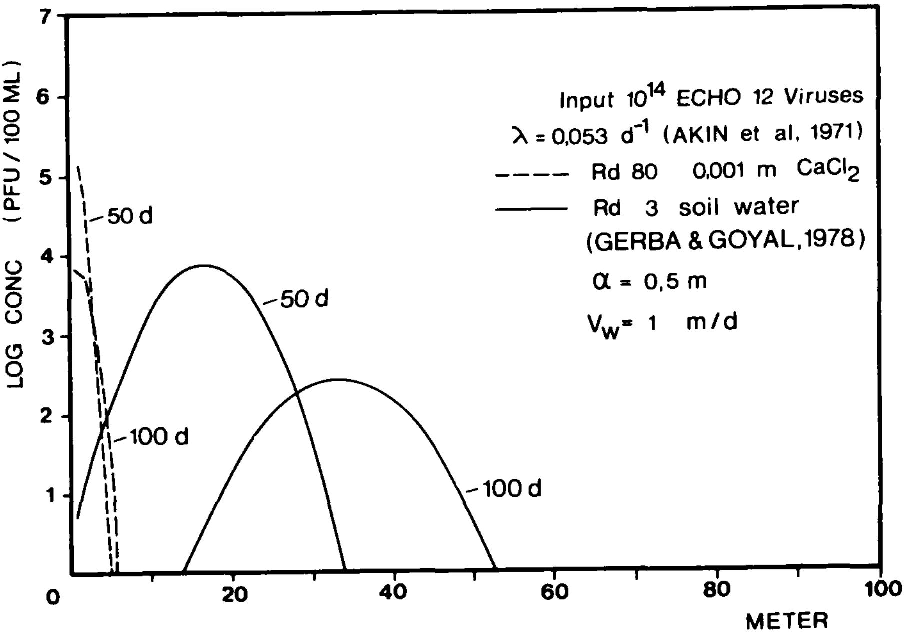

Fig. 1. Model calculation of virus transport in groundwater (single impulse, point source)

Bacteria can attach themselves actively on the surface of the solid aquifer materials. The attached bacteria are protected against other influences and find higher nutrient concentrations, which decrease the elemination rate. The investigations with autochthonic bacteria show that the attachment is most intensive in the phase of exponential growth. The enteric bacteria show hardly any growth in groundwater, thus the active attachment should be at a minimum.

Polluted groundwater plumes undergo dispersion which causes a distribution of the pollutants in time and space so that in the comtaminated groundwater body the concentration decreases in time and with transport distance. This process may be described by the general transport equation in vectorial form (Ref. 9).

$$\frac{\partial C}{\partial t} = \text{div}\left(\frac{D}{R_d} \cdot \text{grad } C - \frac{V_w}{R_d} \cdot \text{grad } C\right) - \lambda C \qquad (4)$$

D is the coefficient of hydrodynamic dispersion

$D = D' + D_d + D_e$

(D' = coefficient of dispersion, D_d = coefficient of diffusion (important for viruses), D_e = coefficient of active mobility of the bacteria), grad C is the concentration gradient.

V_w the average groundwater velocity, λ the elimination rate and R_d the retardation factor (eqn. 3). The active mobility of the bacteria decreases with decreasing temperatures (e.g. for E.coli 0.1 m/d at 20^oC). The hydrodynamic coefficient D depends on groundwater flow velocity (Ref. 10).

$$D = \alpha \cdot v^a + b \qquad (5)$$

The dispersivity coefficient α is a function of the inhomogeneity of the aquifer, thus α increases with the scale of the experiments. Porous media used in laboratory experiments have dispersivity coefficients α in the order of 1 cm - 1 m, in field experiments in the order of 0,1 m - 100 m, and in the fissured and karstic rocks 10 m - 1000 m (Ref. 4). For given boundary conditions, numerical models are available. By inserting the above mentioned dispersivities it can be shown that in fissured and karstic aquifers a "purification" of groundwater occurs due to dilution below detection level although the residence time in these aquifers may be too small for an effective elimination and the filtering qualities are generally poor.

Model calculations of bacteria transport using laboratory data, indicate that under certain conditions bacteria can be transported over large distances. In fact coliform bacteria were observed to be transported in loamy sand aquifer for more than 1 km, and in fissured karstic aquifers for more than a few kilometers. Thus, depending on all the factors mentioned above, very different transport times and distances can occur. Many of these controlling factors need further intensive laboratory and field investigations, furthermore theoretical model calculations with different parameters should be done.

FILTRATION AND SUFFOSION

The microorganism transport may also be limited by the pore size and the size of the microorganism. Calculations of suffosion can be used for the mechanical filtering criteria (Ref. 4). Thereafter the mechanical filter processes in gravelly aquifers cannot be very effective due to the small diameters of bacteria (0.2 - 5 µm) and viruses (0.25 - 0.02 µm). The critical pore diameter for particle transport, which describes the limiting pore size, in medium sand is calculated to be 72 µm. For the bacteria a mechanical filtration should be expected below the grain size of coarse loam with uniform grain size distribution. In natural sediments the grain size distribution is more heterogeneous, in which some percentage of the pore diameters can interfere with bacteria transport (> 10 % in sand) (Fig. 2). The particle accumulation on solid substance surfaces is affected by sedimentation, flow processes, diffusion and interception (Ref. 11, Figs. 3,4)

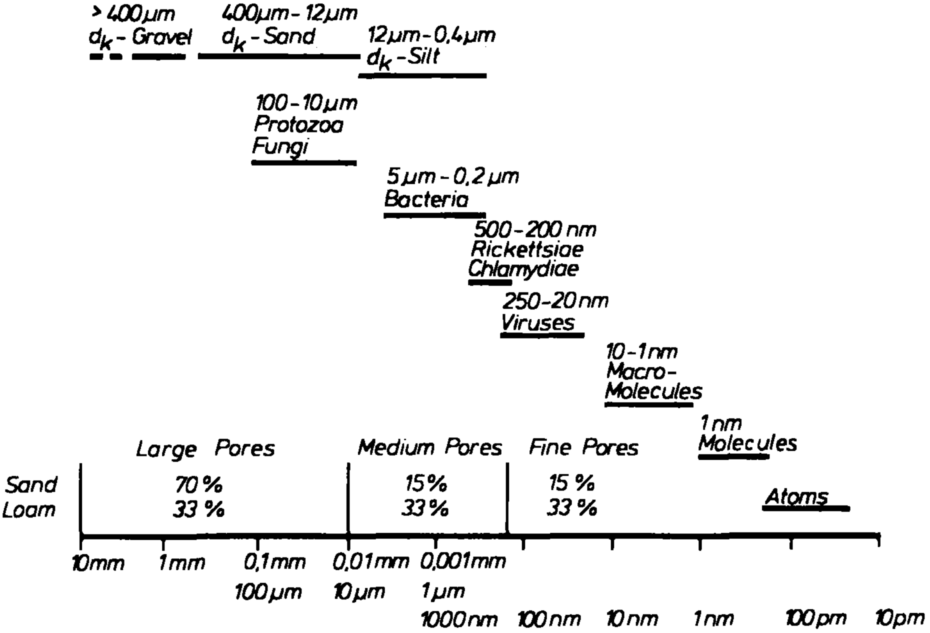

Fig. 2. Comparison of grain size, pore size and size of microorganisms

The importance of sedimentation for bacteria and viruses has been apparently overestimated in the past: the sedimentation is very important for the accumulation of inorganic mineral suspension

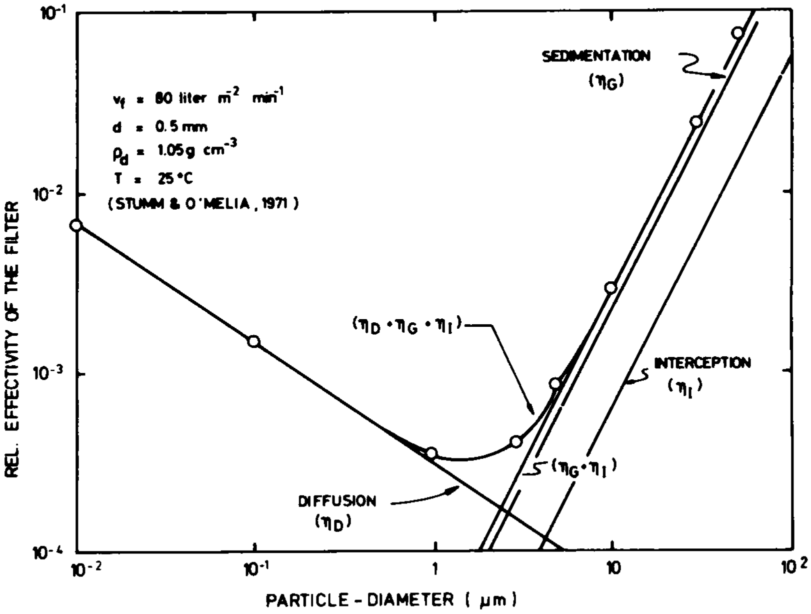

Fig.3.Mechanisms of the filtration processes

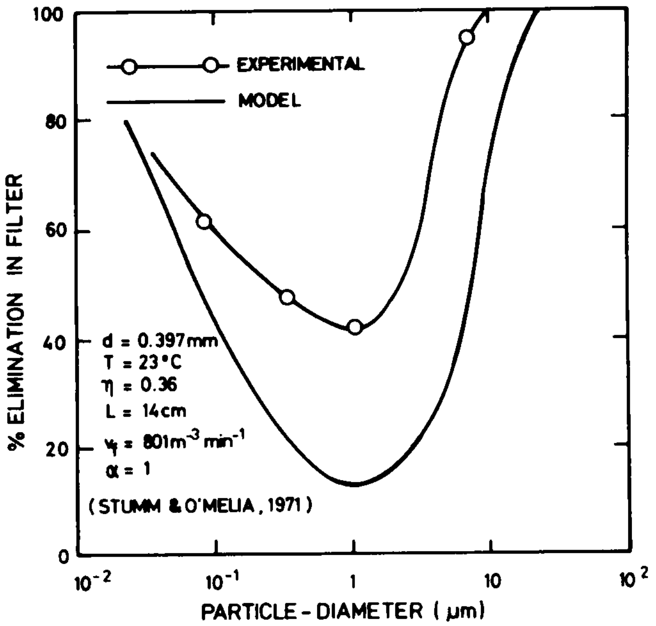

Fig.4.Model calculation and experimental results of filtration effectivity

(density about 2,5 g/cm^3), but not for microorganisms (density about 1 g/cm^3). The kinetic energy of a small particle which is transported by the groundwater flow to the surface of a grain is not high enough to overcome the repulsive surface forces.

For particles with diameters of less than 1 µm (e.g. viruses) the diffusion is very important, becoming increasing effective with decreasing particle size. The interception is the most effective process for the bacteria although this process has its minimum at particle diameters of about 1 µm. As bonding forces act mainly VAN DER WAAL forces (mass) and COULOMB (electrostatical) forces. The effects of VAN DER WAAL forces are restricted to very short distances ($r \leq$ few nm), and their power decreases rapidly with increasing distances ($\sim 1/r^7$), whereas the COULOMB forces decrease much less with increasing distances ($\sim 1/r^2$).

The solid particles of an aquifer are usually negatively charged. An exception are the iron and manganese hydroxides and organic substances at low pH-values. The generally negatively charged bacteria and viruses are strongly adsorbed by anionic adsorbents and only slightly by cationic adsorbents. It is well-known from filtering processes that the negatively charged particles stay in suspension in sandfilters, as the repulsive electrostatical forces are stronger than the VAN DER WAAL forces. The dissolved cations in water decrease the repulsive forces of the grain surfaces. Monovalent cations are adsorbed by the solid substance and decrease their charge deficiency. Under these conditions, the mass forces are more effective and an accumulation of particles can take place. This can be demonstrated by the dependence of virus adsorption on the solute concentration of the water (Ref. 7).

Bivalent cations can also cause a positive charge deficiency so that the electrostatic forces can be more efficient. Thus higher calcium concentrations increase bacteria and virus adsorption.

CONCLUSIONS

The good purifying characteristics of river bank filtration and slow sand filtration can only be partly compared with the processes in groundwater. The biologically active layer at the boundary water/sediment is very effective due to the high content of sorptive small particles and microbial slimes. It needs a certain time to build up this layer.

Disturbaces such as erosion or drying, lead to a breakthrough of the contamination into the deeper layers, which will decrease after some time. During a continous contamination of the groundwater by organic substances and microorganisms the contamination plume becames smaller with time. At very high bacteria concentrations flocculation and aggregation can occur at the source of contamination so that only a limited transport into the aquifer can take place. Thereafter the medium concentration contaminations, which initially enter a groundwater biotop of moderate biological activity, are potentially the worse contaminations.

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