

CHAPTER II

REVIEW –STATE OF THE ART

(...) «Y siempre reinterpretamos y recordamos el pasado desde los acontecimientos que siguieron después, siempre coloreamos un incidente con el conocimiento que no teníamos cuando estaba sucediendo.» (page 172)

ARIEL DORFMAN (from “Heading South, Looking North”. 1998)

This chapter contains a brief summary of the state of the art on clogging. It is not purported to be an exhaustive review, but a compendium of the basic principles and, especially, the most interesting models. There exist excellent reviews in the literature providing further information on physical clogging (HERIZG ET AL., 1970; OSEI-BONSU, 1996; RYAN & ELIMELECH, 1996) and bioclogging (BAVEYE ET AL., 1998; HOLM, 1999), apart from a few comprehensive reviews (PÉREZ-PARICIO & CARRERA, 1999a). This chapter is based on the latter, even though a shorter version is presented in PÉREZ-PARICIO & CARRERA (1998b).

The chapter focuses on conceptual issues (processes, parameters), prevention-redevelopment and modelling. The main objective of this presentation consists in establishing the conceptual framework of clogging and remarking the existing drawbacks, so as to implicitly motivate the need for an integrated approach to the problem.

A remark has to be done before initiating the Chapter. From a conceptual point of view, there is no difference between surface (basins) and deep (wells) recharge systems, because the physics of the processes are equivalent in both types of systems. However, there are evident practical implications, since the operational procedures, requirements on the quality of recharge water and objectives may vary substantially. This will be taken into account when referring to technological aspects.

2.1. CONCEPTUAL ASPECTS

The elementary clogging mechanisms have been listed in Chapter 1 (Introduction). This section provides more details about such mechanisms, as well as enumerating some relevant parameters.

2.1.1. PHYSICAL CLOGGING

The term physical clogging refers to mechanisms that affect the movement, attachment (also deposition, retention, colmatage) and detachment (also shear, unclogging, decolmatage) of inert suspended particles in recharge water, whose consequence is a diminution of porosity. The reviews by HERZIG ET AL. (1970) and MC DOWELL-BOYER ET AL. (1986) are especially recommended. Depending on their size, suspended particles are usually classified under three categories: colloidal, intermediate and large particles.

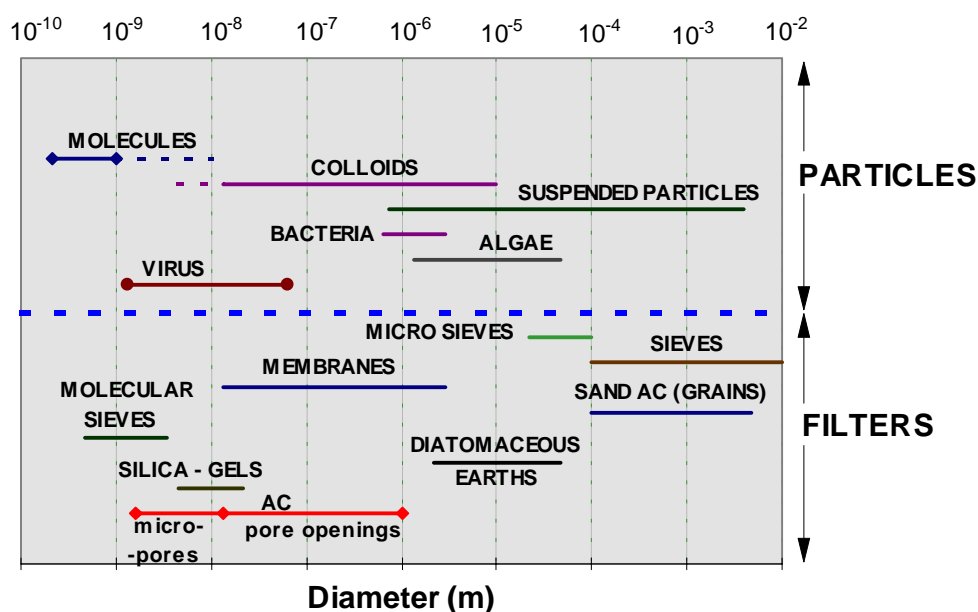


Figure 2.1. Classification of particles and filters as a function of size: diameter and pores, respectively.

Delimitation of some categories is neither universal nor easy to establish. Dashed lines indicate diffuse separations of especial cases. AC stands for activated carbon filters.

2.1.1.1. Colloidal particles

Their diameter is lower than approximately one micron ($1 \mu\text{m} = 10^{-6} \text{ m}$), although $0.45 \mu\text{m}$ is often used as threshold for classification purposes. In fact, Figure 2.1. assumes a limiting value of $10 \mu\text{m}$. Owing to their great specific surface (surface divided by volume), suspension of these particles is controlled by physiochemical surface forces: London-van der Waals attractive forces, attractive or repulsive electrostatic forces and Born repulsive forces. The former are caused by electrical dipoles, while the latter are due to overlapping of electron orbitals (i.e., very short-range interaction, a few nanometers; $1 \text{ nm} = 10^{-9} \text{ m}$). Several theories have been developed to account for these interactions; one of the most famous ones is the DLVO (Derjaguin-Landau-Verwey-Overbeek) theory for total potential energy of interaction between surfaces. Brownian diffusion plays also a relevant role in the fate of colloidal particles in porous media.

The role of colloids in transport of some species comes periodically under scrutiny (HOFMAN & SCHÖTTLER, 1998). It has been shown that radionuclides and metals can get adsorbed to colloids through ion exchange or surface complexation (CORAPCIOGLU & JIANG, 1996; RYAN & ELIMELECH, 1996). This is very important to assess the mobility of contaminants in subsurface environments (FRYCKLUND, 1999). That is, contaminants that would otherwise be immobile may become mobile if attached to a colloid. On the other hand, the number and mobility of colloids is usually low.

Field studies show that colloids may be formed by inorganic compounds such as minerals, oxides and carbonates, or by humic substances and microbial exudates. Natural concentration of colloids in groundwater is usually low, but colloids can be generated by means of:

1. Changes in the solution chemistry that cause repulsive interactions between colloids and formation grains (KALLAY ET AL., 1987; MC DOWELL-BOYER, 1992; RYAN & GSCHWEND, 1994). Two factors must be considered: variations in ionic strength and in pH.
 - On one hand, when recharge water has a lower ionic strength than groundwater the inter-particle repulsion increases and induces the remobilisation of colloids (QUIRK & SCHOFIELD, 1955; MC NEAL & COLEMAN, 1966; ABU-SHARAR ET AL., 1987). Clay swelling and dispersion is associated to this phenomenon. GOLDENBERG ET AL. (1983, 1984) have reported great reductions in permeability due to a reduction in groundwater salinity. KHILAR & FOGLER (1984) define a critical salt concentration value for particle dispersion in Berea cores (with monovalent cations) as a function of temperature and cation type.
 - On the other hand, an augment of pH tends to enhance clay dispersion and to reduce the intrinsic permeability of the medium.
2. An increase in groundwater velocity due to rapid flow through fractures or to pumping, that is, as a result of hydrodynamic changes (KAPLAN ET AL., 1993; BACKHUS ET AL., 1993; RYAN ET AL., 1995). This is why sampling colloids –and colloids-sized microorganisms- in aquifers requires special protocols (HOFMAN & ESCHWEILER, 1999)

2.1.1.2. Intermediate particles

Their diameter varies between 1 and 30 μm , so that they are subject to both surface and volumetric forces. Surface forces can be neglected for diameters larger than 10 μm (SANFORD & GATES, 1956), even though some authors state either that van der Waals forces are significant (MINTZ, 1964; MACKRLE, 1960) or even that electrokinetic forces must be included too (STANLEY, 1955; O'MELIA & CRAPPS, 1964; IVES, 1965).

For the same reason, sedimentation is also controversial. Some authors consider it (CAMP, 1937; FAIR, 1951; IVES, 1961), whilst others neglect it (STEIN, 1940; O'MELIA & CRAPPS, 1964; SMITH, 1967). Other researchers restrict the importance of sedimentation to aggregates (DIAPER & IVES, 1965; ISON & IVES, 1969).

It is evident that discrepancies arise when dealing with particles that can not be clearly associated to a specific group, that is, when both surface and volumetric forces can be relevant. It seems though that both surface forces and sedimentation should not be neglected.

2.1.1.3. Large particles

Their diameter is larger than 30 μm and are only affected by volumetric forces. Therefore, relevant processes include sedimentation, direct interception (straining) and hydrodynamic effects. Large particles get retained in crevices, constriction sites and caverns. Some authors state that spontaneous unclogging of large particles is improbable in natural conditions, even if

flow is increased by a factor of 3 or 4 (MAROUDAS, 1961; SAKTHIVADIVEL, 1966; HERZIG ET AL., 1970).

It is also important to notice that some authors incorporate ‘mechanical jamming’, that is, particle rearrangement, into another clogging category (SNIEGOCKI & BROWN, 1970; LEENHEER ET AL., 1976; JOHNSON, 1981; HUISMAN & OLSTHOORN, 1983; RANDALL, 1995). PYNE (1989) and JENNE ET AL. (1992) include clay expansion or dispersion. But, as commented for colloidal particles, mechanical jamming and clay swelling plus dispersion can be viewed as particular cases of physical clogging. Sometimes particulate organic matter (CUSTODIO, 1981; PAVELIC & DILLON, 1996) can also provoke a specific flow reduction.

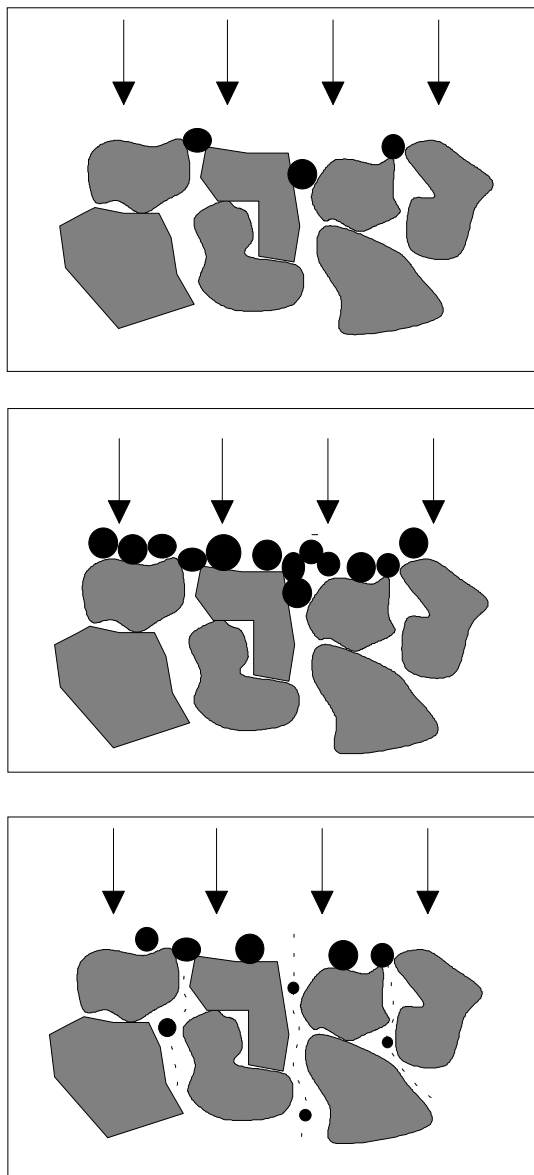


Figure 2.2. Mechanisms during water filtration.

At the beginning, blocking filtration (top) takes place when the particles' diameter is larger than the pores. Then, cake filtration (middle) proceeds as the previously retained particles lodge other mobile particles. This can occur with or without compression of the cake itself (not explicitly shown). Deep bed filtration (bottom) is the fourth mechanism, and occurs when the particles can travel a certain distance through the medium until they are deposited by different causes. These mechanisms are not necessarily sequential.

When water flows through a permeable medium several types of accumulation of sediments can take place (Figure 2.2.):

1. *Blocking filtration* occurs when a particle obstructs an opening or pore due to interception. This originates an increase in head loss and a diminution in filtration rate.
2. *Cake filtration without compression* takes place when other particles are deposited on the previously blocked particles. A cake or clogging layer develops on top of the soil filter. This is a typical phenomenon in surface Artificial Recharge systems.
3. *Cake filtration with compression* occurs when the clogging layer is compressed during accumulation of particles.
4. *Deep bed filtration* is characteristic of recharge wells, yet it can be relevant for surface systems too. Particles smaller than the medium pores travel a certain distance across that medium, and can be deposited by several capture processes during their passage (deep bed filtration).

How these mechanisms work depends on the type and characteristics of the medium, recharge water quality, type (size and physicochemical properties) of the sediments and the infiltration extent. A generic equation can be used to describe the first three mechanisms, whilst the latter will be investigated in section 2.3.2. ORR (1977) proposed the following generic equation:

$$\frac{d^2V}{dt^2} = \alpha_1 \left(\frac{dV}{dt} \right)^{\alpha_2} \quad [2.1.]$$

where t [T] is time; V [L^3] is the recharge volume; α_1 [dimension depending on the mechanism] is a coefficient used to define the mechanism and α_2 [L^0] is a constant that determines the actual filtration mechanism.

- If $\alpha_2=0$, equation [2.1.] describes the mechanism of cake filtration. After integration, it yields:

$$\frac{t}{V} = \frac{\mu_1 R_0}{\Delta P A_F} + \frac{\mu_1 I_F}{2 \Delta P A_F^2} V \quad [2.2.]$$

where μ_1 [$ML^{-1}T^{-1}$] is the dynamic viscosity of the liquid; R_0 [L^{-1}] is the initial resistivity of the (clean) filter; P [$ML^{-1}T^{-2}$] is the applied pressure, Δ denoting increment; A_F [L^2] is the membrane filtering area; and I_F [L^{-2}] is a measure of the membrane fouling potential of water (SCHIPPERS & VERDOUW, 1980). Equation [2.2.] shows a linear dependency of the inverse of flowrate, t/V with respect to the filtered volume, V . The slope of this term is defined as the modified fouling index (MFI), described in section (2.2.3.):

$$MFI = \frac{\mu_1 I_F}{2 \Delta P A_F^2} \quad [2.3.]$$

This parameter –which equals α_1 in equation [2.1.]– is very important for clogging purposes. The MFI [TL^{-6}] is commonly expressed in $s \cdot L^{-2}$. It is possible to use the same equation for cake filtration with compression if the MFI is multiplied by a factor that incorporates the compressibility of the solids:

$$MFI|_{\text{compr}} = MFI \left(1 + \Delta P^{\beta_p} \right) \quad [2.4.]$$

where β_p [L^0] is a constant that contains the dependence on the compressibility of the particles.

- If $\alpha_2=2$, equation [2.1] reduces to the expression for blocking filtration and α_1 equals:

$$\alpha_1 = \frac{\Delta P A_F N_p}{\mu_1 \varepsilon_F} \quad [2.5.]$$

where N_p [L^{-3}] is the number of particles per unit volume (concentration) and ε_F [L^{-1}] is a constant that depends upon the structure of the membrane filter.

- An intermediate value of α_2 ($\alpha_2=1$) indicates that there is a partial pre-blocking of the pores followed by cake filtration.

2.1.2. BIOLOGICAL GROWTH (BIOCLOGGING)

Although protozoa and viruses are present in groundwater and in fact are receiving a great deal of attention because sanitary concerns, bacteria play the most relevant role regarding biological clogging. CHAPPELLE (1992) and PAVELIC ET AL. (1996) provide further information about microorganisms and groundwater, but many studies are available (REFSGAARD ET AL., 1991; ALBRECHTSEN & WINDING, 1992; SCHOETTLER & SCHULTE-EBBERT, 1995).

In a detailed review on biological clogging, BAVEYE ET AL. (1998) identify four main mechanisms of bacterial clogging. These are (1) the accumulation of cell bodies in the porous medium, (2) the production of bacterial extracellular polymers, basically polysaccharides, (3) the entrapment of gaseous products, especially carbon dioxide (respiration), nitrogen (denitrification) and methane (methanogenesis), and (4) the microbially mediated accumulation of insoluble precipitates.

Many bacteria form a biofilm, which is composed by cells and extracellular material, basically polysaccharides (ALLISON, 1947; SHAW ET AL., 1985). The biofilm is treated as a separated phase by many researchers (TAYLOR & JAFFÉ, 1990a). The formation of a biofilm attached to the medium reduces the porosity, thus causing clogging of Artificial Recharge devices.

Bacteria are also important because of their catalytic capacity with respect to redox reactions. Bacteria need external electron acceptors for catabolism, and carbon (organic if heterotrophic and inorganic if autotrophic) for synthesis. Oxygen is the most effective electron acceptor in terms of energetic yield, so that its availability is crucial for bacterial development. Generation, transport and consumption of certain basic species depend strongly on bacteria and aquifer conditions. Each year new bacteria types are being identified in field studies (TAYLOR ET AL., 1997; ESCHWEILER ET AL., 1998), which confirms the importance of this clogging mechanism.

Algae are one of the concerns for surface systems. Clogging by algal growth can be very severe, as reported elsewhere. For instance, *Synedra* (size between 65 and 85 μm) and *Nitzschia* (150 μm) have been detected by KONNO & SATO (1986) and ADIN & CHELMINSKY (1986), respectively. Algal activity concentrates in a surface layer, mainly within the upper 7.5 cm (GOODRICH ET AL., 1990). Photosynthesis sometimes originates precipitation of carbonates as well, because consumption of carbon dioxide can lead to over-saturation of carbonaceous compounds -mainly calcite.

2.1.3. CHEMICAL REACTIONS

Chemical reactions that promote the precipitation of minerals can occur because of incompatibility between recharge water and groundwater (LLURIA ET AL., 1991; HUISMAN & OLSTHOORN, 1983;

PETERS, 1994; and many other researchers). The precipitation of minerals provokes an immediate reduction in porosity.

Chemical clogging of continuous recharge wells is unlikely, because groundwater is displaced by recharge water and mixing takes place only at the recharged water front. Instead, pumping wells are more susceptible. For instance, under reducing conditions, iron may be dissolved. Oxidation will then cause the precipitation of iron compounds (STUYFZAND, 1993). This type of reactions is usually catalysed by bacteria. Thus, it is difficult to uncouple chemical and biological processes in many real situations.

Chemical composition of recharge water and groundwater, aquifer mineralogy and physical variables (temperature and pressure) control precipitation. Reactive surface area of a mineral dictates the rate of precipitation or dissolution. Surface area is essential, as explained in section 2.4. Moreover, bacterial metabolism, addition or depletion of oxygen and carbon dioxide, and presence of catalysts affect mineral precipitation and dissolution.

2.1.4. GENERATION OF GAS AND AIR

Gas can be originated by biochemical reactions in both surface and deep systems. Temperature increases or pressure decreases can lead to releases of dissolved gases as well. On one hand, temperature of recharge water should be kept above groundwater temperature because the solubility of gases decreases with temperature. On the other hand, gas solubility is directly proportional to pressure. "Bubbling" takes place when the water becomes over-saturated with gas and this separates from the liquid in the form of bubbles. Negative (below atmospheric) pressures must be prevented in pipelines carrying water to recharge wells in order to avoid bubbling of dissolved gases. These phenomena are characteristic of pumping wells, where positive pressures must be preserved.

Two main sources of air exist in wells (OLSTHOORN, 1982): first, bubbling due to the free fall of water inside a recharge well (cascading) and, second, air entrance into the well if negative (i.e., below atmospheric) pressures occur. Entrained air bubbles can move downward and get into the aquifer formation, increasing the resistance to water flow and resulting in higher water levels inside the well. Such a resistance build-up is usually quite rapid, although it levels off after some hours have passed because bubbles redissolve into the water.

Release of dissolved gases is another problem, because gas binding can take place. Air entrainment in wells can be avoided through an adequate design and operation of recharge wells. Prevention of negative pressures is done either by maintaining positive pressures in the pump column prior to discharge below the water level or by means of airtight systems.

In spite that air is generally a nuisance for recharge wells, it is also purported to be a problem in surface systems. According to NIELSEN ET AL. (1986) "situations can occur where air is not free to escape when it is displaced by water, thus leading to larger soil air pressures and increased resistance to liquid flow. The most obvious situation is that of ponded infiltration over large areas, especially in the presence of high (or perched) water tables or relatively impermeable soil layers".

A third means of augmenting the extent of gaseous phase consists of bacterial metabolic products. When biocatalysed reactions take place, an increase of certain species can occur. Gas will be generated if oversaturation is achieved.

2.1.5. COMPACTION

This is a relatively rare case that only takes place in surface systems, mainly basins (BOUWER & RICE, 1989; BOUWER, 1990). Compaction is due to an excess of water above ground level in surface systems, which causes the clogging layer to compress by increasing the confining pressure.

In theory, increasing the water height has a direct incidence in hydraulic gradient and recharge rate should augment too. But the clogging layer formed as a result of sieving of suspended particles and algae offers a resistance to flow that is increased if compression occurs. The final effect, as described below, is a reduction in porosity. In fact, the top sediment layer on sand filters of water treatment plants can break down as a result of an unduly increase of the hydraulic gradient. This causes particles to contaminate and spoil the filter.

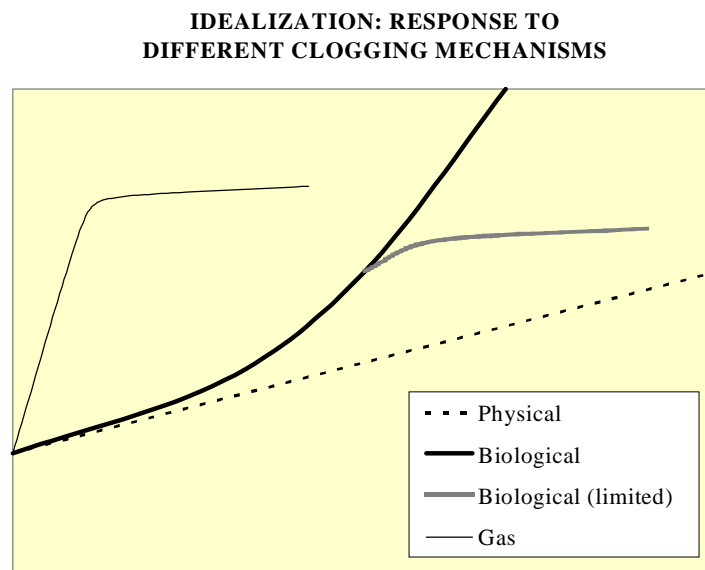


Figure 2.3. Clogging evolution as a function of the predominant process.

It is a conceptual distinction, but shows differences caused by different clogging sources. (Modified from PYNE, 1995). W represents the resistance (pressure build-up divided by flowrate times the viscosity), as introduced by OLSTHOORN (1982), due to clogging.

2.1.6. INTER-DEPENDENCE OF CLOGGING MECHANISMS

Previous identification of individual processes is required in order to understand the basic clogging mechanisms (Figure 2.3.). But these processes have a mutual influence in practical conditions (Table 2.1.):

(i) Coupling particles-biology.

ERNISEE & ABBOTT (1975) and ROSOWSKI ET AL. (1986) mention the interaction between microbial communities and colloidal mineral particles. AVNIMELECH & MENZEL (1983) report the evidence of algal-clay flocculation.

(ii) Coupling particles-chemistry.

Colloids are subjected to surface forces that depend on chemical parameters such as ionic strength. KHILAR & FOGLER (1987) detected clogging by formation and migration of fines, colloids and precipitates. The origin of fines can be 'chemical', for instance coming from calcite dissolution (PAVELIC & DILLON, 1996).

(iii) Biochemical coupling.

It is the most evident link attending to the catalysing effect of bacteria (JOHNSON, 1981). Specific models have been proposed (BRUN ET AL., 1994; for instance).

Algal photosynthesis usually causes an increase in pH that, in turn, produces precipitation of carbonates (DAVIS, 1989; BOUWER & RICE, 1989). This is especially important when pre-treatment includes coagulation that requires pH correction. In that case, the surface water may become calcite oversaturated or more saturated, prior to algal growth (STUYFZAND, 1986, 1989).

(iv) Biology-gas coupling.

Metabolic products of bacterial reactions can transfer to the gaseous phase if oversaturation exists. For instance, denitrification gases during basin management have been found to cause a remarkable clogging. (RICE, 1974; BOUWER & RICE, 1989). Algal photosynthesis is also an important process that leads to oxygen production and carbon dioxide consumption.

(v) Chemistry-gas relations.

Supply of oxygen can accelerate iron precipitation (CUSTODIO, 1981; SHAVER & WUCETICH, 1995), while a carbon dioxide loss often conducts to carbonate precipitation (DEGALLIER, 1987). A good representation of this phenomenon is given by THEISS & SINGER (1974), who studied the relationship among iron, organic matter and oxygen .

(vi) Compression and algal growth.

An excess of water height above the soil of basins creates a compressive force which diminishes infiltration rate, enhancing algae proliferation. Algal photosynthesis increases pH, so that calcite precipitation is possible (BOUWER, 1990).

Table 2.1. Inter-dependence of clogging mechanisms.

Only connections cited in the text are included. The remaining relationships are not considered and hyphens (-) are used.

PHYSICAL	BIOLOGICAL	CHEMICAL	GAS	COMPACTION	
	Coloid-Bacteria Algae-Clay	Surface Forces and Chemistry	-	-	PHYSICAL
		Biocatalysts Photosynthesis	Bacterial products	-	BIOLOGICAL
			Addition of O ₂ Loss of CO ₂	Compression => precipitation	CHEMICAL
				-	GAS
					COMPACTION

2.2. PREVENTION AND REDEVELOPMENT

Prevention is essential to minimise clogging. However, after a certain recharge period -whose duration depends on design, water quality and environmental and hydrogeological conditions- it is often necessary to apply a redevelopment method. Both topics are addressed in this section.

2.2.1. PREVENTION

The best preventive tactics consists of ideal design of systems together with high water quality and optimum hydrogeological characteristics. Actual recharge facilities are not ideal, though. This is why various measures must be adopted to maximise benefits. As shown in Table 2.2., some of these are strictly necessary to obtain a satisfactory groundwater quality, preserving it from pollution. Details about numerical constraints on certain parameters are presented in section 2.2.4.

Table 2.2. Summary of preventive measures depending on the dominant clogging processes.

PHYSICAL CLOGGING	Coagulation-flocculation plus sedimentation prior to recharge Prior filtration to eliminate particles → sand filters, microfiltration Deep systems → Periodic backwashing to detach sediments Surface systems → Desiccation of basins (i.e. recharge cycles)
BIOCLOGGING	Bacteria: <ul style="list-style-type: none"> - Disinfectants - Reduction of nutrients - Constraints on input concentration (TOC...) Algae ⇔ (surface systems) : <ul style="list-style-type: none"> - Prefiltration - Reduction of nutrients - Chemicals - Avoid direct light on the water surface
CHEMICAL CLOGGING	Acidification Daily pumping Separate strata Avoid oxygen
GAS GENERATION	Adequate design (valves, positive pressures) Recharge water temperature > Groundwater temperature
COMPACTION	Limit water height (⇔ surface systems)
CORROSION	Avoid: Work-hardened materials & Stressed parts High temperature & recharge rate Oxidising conditions
GENERIC RULES	<ol style="list-style-type: none"> 1. Appropriate water treatment 2. Minimise aeration (wells) 3. Proper design 4. Install high-water alarms

Table 2.2. includes different possibilities that are not mutually exclusive. In general, it has been observed that surface systems can maintain high yields if recharge cycles are applied, that is, if the clogging material is allowed to dry and crack naturally. This tends to break clogging deposits, as well as impairing algal growth and enhancing biodegradation within the non-saturated zone. As for deep systems, the best management option consists of periodic backflushing (reversing flow direction by pumping). In both cases, prefiltration can be very helpful. WEGELIN ET AL. (1991) provide guidelines on horizontal roughing filters, which are simple, effective and inexpensive.

2.2.2. REDEVELOPMENT

Although prevention is a key aspect in the design and management of recharge plants, often it is not enough to maintain the efficiency of the system at an adequate level. Prior to the occurrence of notable clogging impacts, it is necessary to redevelop the recharge system. In fact, redevelopment and prevention may not be separable in practical situations, because such distinction is quite arbitrary. For instance, management alternatives such as desiccation or periodic backflushing can be indistinctly considered as preventive or redeveloping measures. Table 2.3. shows redevelopment techniques (OLSTHOORN, 1982; DRISCOLL, 1986) but, contrary to preventive measures, a clear distinction is made between surface and deep systems. The distinction is due to technological differences between them rather than to conceptual dissimilarities.

Table 2.3. Redevelopment techniques for surface and deep systems.

This distinction is motivated by the practical implications in real recharge plants, even though the processes involved are identical. Recharge cycles are usually implemented in surface systems, which leads to the classification in preliminary and during-operation techniques. As for deep systems, redevelopment methods depend on the type of clogging processes.

Surface systems	During runs:	<ul style="list-style-type: none"> - Filtration: mats, filters - Chemicals (calcium) - Enhance natural factors: aeration, avoid light - Others: underwater robot to scrape the clogging layer
	Between runs:	<ul style="list-style-type: none"> - Mechanical methods: tillage, scrapping - Addition of chemicals (calcium) - Natural methods: drying of basins, freezing - Acid baths to remove carbonated deposits
Deep systems	Generic methods	<ul style="list-style-type: none"> - Pumping, since flow reversals promote detachment - Dosing of specific chemicals: disinfectants, acids - Methods based on the injection of fluids - Adoption of recharge protocols - Other, less frequent techniques
	Physical clogging	<ul style="list-style-type: none"> - Pumping - Chemicals - Fluid-based methods - Protocols
	Bioclogging	<ul style="list-style-type: none"> - Pumping - Chemicals - Physically-based methods - Combination of methods
	Chemical clogging	<ul style="list-style-type: none"> - Chemicals - Hydro-mechanical methods - TV surveys and scraping borehole walls by brushing

In summary, it can be stated that the following methods are preferable (PÉREZ-PARICIO & CARRERA, 1999a) if combined with hydraulic methods:

- Polyphosphates for physical clogging because they reduce the stability of retained particles, which enhances the efficiency of detachment.
- Addition of chemicals if bioclogging is the dominant process. Chemical oxidants, such as chlorine (Cl₂) or hydrogen peroxide (H₂O₂), promote the inactivation of bacteria.
- Addition of acids for chemical clogging, in order to remove encrustations of different minerals.

Hydraulic methods comprise methods such as pumping, surging or “juttering”. The latter consists of intermittent pumping in the damaged well (OLSTHOORN, 1982).

2.2.3. USEFUL TOOLS

Given the significance of clogging, some authors have tried to find predictive tools. These include specific parameters, relationships and generalised charts. Some of them are briefly described below. Here the aim is to explain their applicability range and main drawbacks. Further information is available in PÉREZ-PARICIO & CARRERA (1999a).

2.2.3.1. Specific parameters

Conventional parameters, such as turbidity and concentration of suspended solids (physical clogging) or dissolved organic carbon (bioclogging), are useful, but they are less informative when recharging high quality water. Alternative parameters have been investigated in the Netherlands:

- (i) Modified fouling index, MFI (SCHIPPERS & VERDOUW, 1980). It is proportional to the concentration of both colloidal and suspended matter, and is determined by membrane measurements. Physically, it represents the slope of inverse filtered flow versus cumulative filtered volume (see section 2.1.1.1.). It is used as a guideline in the Netherlands assuming a maximum MFI value of 3 to 5 s·L⁻² for well recharge in fine sand aquifers. However, some limitations arise: it is only reliable when clogging is strictly physical, and threshold values can only be established after doing field research, taking into account the aquifer characteristics.
- (ii) Assimilable organic carbon, AOC (HIJNEN & VAN DER KOOIJ, 1992). It was introduced to assess the biostability of drinking water (not subject to disinfection in the Netherlands). AOC represents the fraction of organic carbon that can be rapidly assimilated by microorganisms, which may be an oversimplification in field situations.
- (iii) To overcome these and other limitations, another parameter is currently under study (VAN DER KOOIJ ET AL., 1995): the biofilm formation rate, or BFR. This accounts for all biomass in the water, providing an integrated quantification of bioclogging potential (HIJNEN ET AL., 1998).

Despite all limitations, both MFI and AOC (or, alternatively, the BFR) should be considered as excellent clogging-indicators. Although prediction can not be adequately addressed (SCHIPPERS ET AL., 1995), they can indicate whether clogging is to be relevant or not. Furthermore, MFI and AOC measurements can be combined with parallel filters (HIJNEN ET AL., 1998), which refer to standard filter media (i.e. core samples that can be considered to be representative of different lithologies) that are flushed with samples of recharge water. Combining simple measurements with aquifer replica may be a more realistic approach than standard laboratory estimates.

2.2.3.2. Preliminary assessment of clogging in recharge systems

- (i) Normalised build-up (*for recharge wells*). OLSTHOORN (1982) proposed a standardised equation to compare clogging effects in recharge wells under different circumstances. This equation adopts several reference conditions: 20 °C water temperature, infiltration velocity $v_0 = 1$ m/h, injection time $t_0 = 1$ year:

$$\Delta h = \left[h_e \left(\frac{\mu_0}{\mu_e} \right) \left(\frac{v_0}{Q_e / A_F} \right) - h_b \left(\frac{\mu_0}{\mu_b} \right) \left(\frac{v_0}{Q_b / A_F} \right) \right] \left(\frac{v_0 t_0}{V / A_F} \right) \quad [2.6.]$$

where subscripts 0 , b and e refer, respectively, to the standard, initial and final values; h [L] is the piezometric head, so that Δh represents the build-up caused by clogging; v [LT^{-1}] is the infiltration velocity; A_F [L^2] is the well filtering area; and Q [L^3T^{-1}] is recharge flowrate.

- (ii) Simple filtration formulae (*for physical clogging*). Darcy's equation is applicable to clogging when the temporal evolution of permeability (or resistivity, which is the inverse of permeability) can be approximated or fitted to laboratory data. Darcy's law can be directly used to express the time evolution of filtration rate through a membrane (SCHIPPERS & VERDOUW, 1980; RICHAUD & MILLISIC, 1991), as shown in section 2.1.1.1.
- (iii) Parallel filters. Due to the problems associated to previous parameters, a new approach applies simple semi-empirical equations to data recorded during laboratory experiments with parallel filters. These are columns filled-in with aquifer material, dosing recharge water under field-like hydraulic conditions (SCHIPPERS ET AL., 1995).

Parallel filters can provide very valuable estimates of clogging evolution, but it is difficult to extrapolate laboratory conclusions to field conditions. This is especially questionable when natural heterogeneity in the aquifer is high, what is very usual. Consequently, standard media are being tested to enable comparing the clogging potential of water (HIJNEN ET AL., 1998).

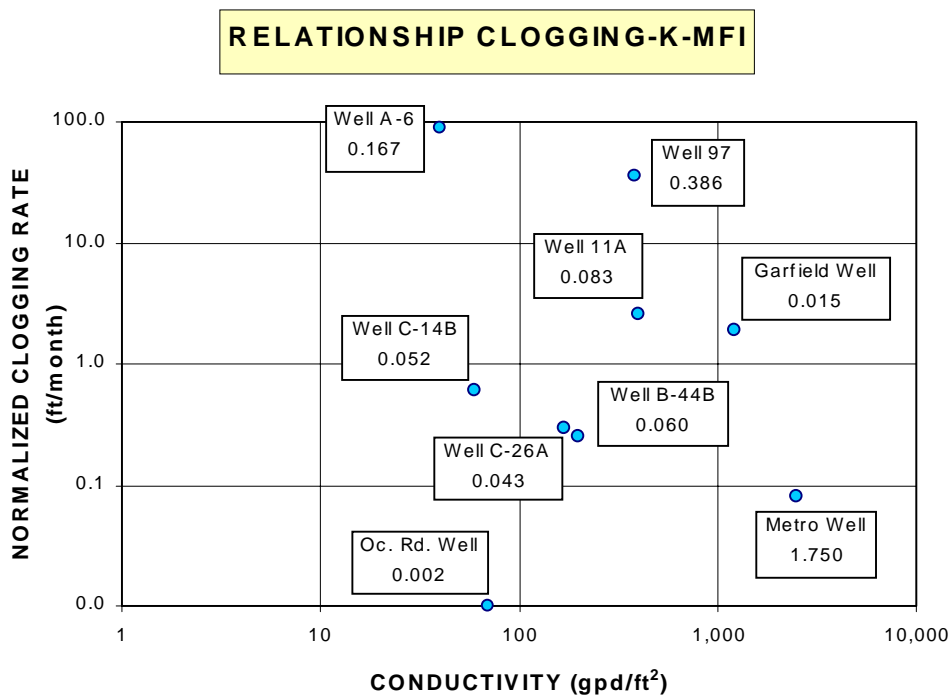


Figure 2.4. Normalised clogging rate versus estimated hydraulic conductivity (HUTCHINSON & RANDALL, 1995).

If the concentration of suspended solids in recharge water is also taken into account, it is possible to observe a relationship among the 3 factors. This is a useful tool for physical clogging in recharge wells, but is not applicable when biochemical processes play a role in the system. (Notice that units are non-metric in this example).

2.2.3.3. Special charts

Only the Hutchinson's plot (HUTCHINSON & RANDALL 1995) is mentioned here, because it is particularly important. It incorporates three different magnitudes, each one related to basic properties of a recharge system: hydraulic conductivity of the aquifer, concentration of suspended particles and clogging (normalised) build-up (Figure 2.4.). Suspended particles can be expressed by

means of conventional parameters such as the total concentration of suspended solids (TSS, usually in $\text{mg}\cdot\text{L}^{-1}$) or other parameters, such as the MFI (in $\text{s}\cdot\text{L}^{-2}$).

Table 2.4. Recommended values for basic parameters.

CONCEPT		LIMITATIONS	COMMENTS
PHYSICAL CLOGGING	Deep Systems	⁹ [TSS] < 2 $\text{mg}\cdot\text{L}^{-1}$	if $K > 40 \text{ m}\cdot\text{d}^{-1}$
		^{1,9} [TSS] < 0.1 $\text{mg}\cdot\text{L}^{-1}$	if $4 \text{ m}\cdot\text{d}^{-1} < K < 40 \text{ m}\cdot\text{d}^{-1}$
		² MFI < 3÷5 $\text{s}\cdot\text{L}^{-2}$	
		^{1,3} Tur < 1 NTU	
	Surface Systems	[TSS] < 10 $\text{mg}\cdot\text{L}^{-1}$ Tur < 5 NTU	
BIOLOGICAL CLOGGING	Deep Systems	⁴ pH > 7.2 (iron bacteria)	
		⁴ Avoid CO ₂	
		⁴ DOC < 2 $\text{mg}\cdot\text{L}^{-1}$	according to Swiss standards
		⁴ Eh > 10 mV	
	Surface Systems	TOC < 10 $\text{mg}\cdot\text{L}^{-1}$	
CHEMICAL CLOGGING		⁶ [Fe ²⁺] _{GW} < 11.2 $\text{mg}\cdot\text{L}^{-1}$ ⁷ [Saturation Index ⁸ Ryznar Index > 7 ⁸ pH < 7.5 ⁸ Low [Ca ²⁺] and [Mg ²⁺] ⁸ TDS < 150 $\text{mg}\cdot\text{L}^{-1}$ ⁸ [Cl ⁻] < 500 $\text{mg}\cdot\text{L}^{-1}$	More important for abstraction than for recharge wells Saturation indexes of minerals are essential.
CORROSION		⁸ DO < 2 $\text{mg}\cdot\text{L}^{-1}$ ⁸ Ryznar Index < 9 ⁸ pH > 7 ⁸ CO ₂ < 50 $\text{mg}\cdot\text{L}^{-1}$ ⁸ [TSS] < 1,000 $\text{mg}\cdot\text{L}^{-1}$ ⁸ Avoid H ₂ S	Applicable to wells and pipes

¹Dutch standards (Peters, pers. comm.); ²Olsthoorn (1995); ³German standards (Schöttler, pers. comm.); ⁴Degalier (1987); ⁵van der Kooij & Hijnen (1990); ⁶Lucas et al. (1995); ⁷Hills et al. (1989); ⁸Ford (1990); ⁹Pyne (1995); ¹⁰Hurni.

2.2.4. RECOMMENDATIONS / GUIDELINES

This section contains recommendations to minimise clogging. The suggested limiting values have been obtained mostly from the literature and from commonly accepted operational practices, while the remaining values were proposed by PÉREZ-PARICIO & CARRERA (1999a).

Table 2.4. displays a set of threshold values, where differences between surface and deep systems are explicitly remarked. Notice that some of these values may be difficult to meet, especially for recharge wells. However, they can be relaxed if other conditions apply (limitations used in the Netherlands are very tight, as there are many fine sand aquifers).

Table 2.5. shows simplified criteria to determine the extent of clogging based on a few simple parameters. Such criteria are only indicative, as not all basic magnitudes are included (light, temperature, other nutrients, hydraulic conductivity, recharge regime). However, suggested values should be accounted for to improve management.

Table 2.5. Guidelines for clogging, based on simple parameters.

	CLOGGING	RECHARGE WATER	REDEVELOPMENT
SURFACE SYSTEMS	SLIGHT	TSS < 10 mg·L ⁻¹ Tur < 5 NTU TOC < 10 mg·L ⁻¹	Natural drying and cracking Once a year: Mechanical
	NOTABLE	TSS = 10÷20 mg·L ⁻¹ TOC = 10÷25 mg·L ⁻¹	Frequent drying and cracking Twice a year: Mechanical
	STRONG	TSS > 20 mg·L ⁻¹ TOC > 25 mg·L ⁻¹	Prefiltration recommended
DEEP SYSTEMS	SLIGHT	TSS < 10 mg·L ⁻¹ Tur < 5 NTU TOC < 10 mg·L ⁻¹	Frequent pumping Surging/Jetting: once a month
	NOTABLE	TSS = 10÷20 mg·L ⁻¹ TOC = 10÷25 mg·L ⁻¹	Pumping once a day Surging/Jetting: once a week
	SEVERE	TSS > 20 mg·L ⁻¹ TOC > 25 mg·L ⁻¹	Daily pumping Adapted protocol

2.3. MODELLING

Quantitative approaches to clogging are basic to provide information about the effectively relevant parameters and interactions. The increasing interest for alternative water management techniques and –especially- for water production industry has motivated the development of physical clogging models. Bioclogging models have received much attention too because of the concern about water quality issues. The recent importance of reactive transport –particularly with respect to deep repositories- has promoted research into reactive transport modelling. In general, all these studies focus on one particular problem.

However, evidence that contaminants may adsorb on colloidal particles and that bacteria play a crucial role in aquatic environments demonstrates the interconnectivity of different processes. But it is not possible to find comprehensive models in relation to clogging of porous media, because current models are concerned about specific individual processes. Most of the models do not concentrate in the time evolution of porous medium properties. Porosity changes are hardly taken into account, despite the great influence on the hydraulic behaviour of real systems.

This section makes a distinction between empirical (phenomenological) and theoretical models. The former are only applicable to specific situations, given the site-dependence in terms of hydrogeology, water quality and environmental properties. Yet, they can be very useful to obtain preliminary assessments of clogging potential. The latter are more sophisticated and require a good deal of data, although can give more insight into the clogging mechanisms and their relative importance, thereby improving our understanding of the whole problem.

A detailed listing of models lies beyond the scope of this document. Further information on modelling of physical clogging can be found in SPIELMAN (1977) and OSEI-BONSU (1996). VANDEVIVERE ET AL. (1995), and HOLM (1999) give insight into fundamental issues of biological clogging models. More comprehensive reviews on clogging modelling can be found in CUSTODIO (1986), TAYLOR & JAFFÉ (1990a), BAVEYE ET AL. (1998) and PÉREZ-PARICIO & CARRERA (1999a).

2.3.1. EMPIRICAL MODELS

Empirical models establish a relationship between the time evolution of pressure build-up or infiltration rate and some key parameters, such as the concentration of suspended solids and organic carbon, for instance. The common feature of these models is that they are extremely site-dependent: climatic conditions, aquifer properties, quality of recharge water and native groundwater, and operational rules make them applicable only to the conditions they have been developed for.

Most of the relationships have been developed for surface systems, although it does not imply that this kind of relationships can not be obtained for deep systems. In this document only a few models are described.

2.3.1.1. Exponential decrease

A generalized equation that properly describes many clogging problems was proposed by BIANCHI ET AL. (1978). This equation is formally identical to the equation introduced by HORTON (1933) to quantify the evolution of the infiltration capacity of a soil with time in rain conditions. This equation, applied to clogging, is as follows:

$$i = i_{\infty} + (i_0 - i_{\infty})e^{-\omega_H t} \quad [2.7.]$$

where i [LT^{-1}] is the infiltration rate, defined as the actual recharged volume per unit area; subscripts 0 and ∞ are referred to the initial and final values, respectively. An empirical or adjustable parameter, ω_H [T^{-1}], controls the velocity of clogging. Similar equations, without the asymptotic term, had already been used in the 50's (BOUCHER, 1947) to describe the clogging impact on surface systems. Figure 2.5. shows the typical evolution of infiltration rate.

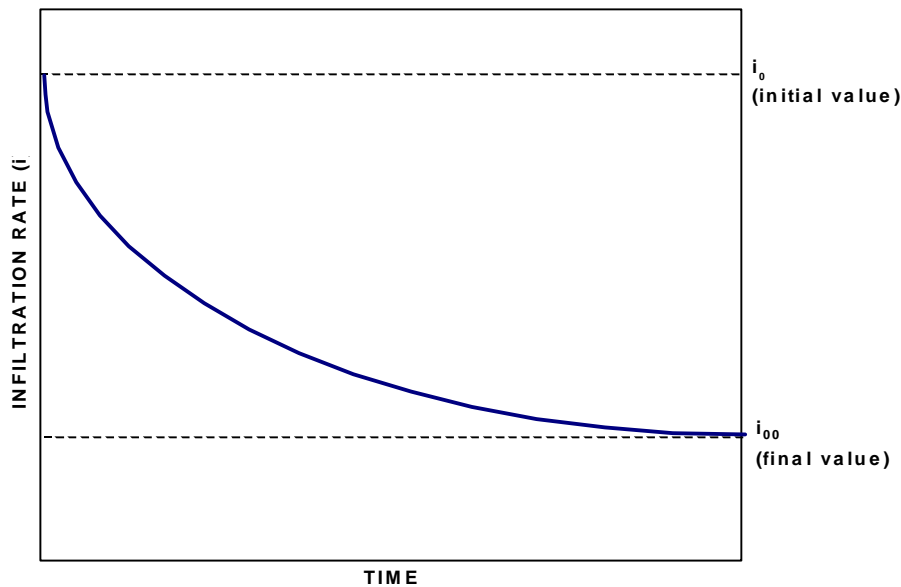


Figure 2.5. Plot of HORTON-type equation with final asymptotic value.

Equation [2.7] has been successfully applied to biological clogging too (SCOTT ET AL., 1974). In that case, the constant ω_H (clogging constant) represents the biological growth constant rate when there is no competition and the substrate (food) is unlimited. IVES (1975) stated that a linear relation between pressure drop and filtration time should be used for initial times; after this time lag, surface filtration starts and BOUCHER's law should be used. There exist variations on Boucher's law, such as the use of power series (PHILIP, 1969) and potential decrease expressions, like KOSTIAKOV's equation (CHILDS, 1967)

2.3.1.2. Site-dependent equations

There are many site-specific relationships whose aim is to find a correlation between the time evolution of key variables and a few measurable parameters. Only some of them are presented here.

One of the classical relationships consists of correlating the infiltration rate with the concentration of suspended solids. For instance, this was done for the Peoria aquifer (CUSTODIO, 1986), where the ratio of suspended matter reduction, χ [L^0], was used as a parameter. The removal of suspended matter during infiltration was assumed to be constant along time, as indicated by HARMESON ET AL (1968):

$$\chi = 1.000 - 0.027B_p^{-0.25} (i \cdot TSS)^{0.33} d_g \quad [2.8.]$$

where B_p [L], *in m*, is the width of the filter material; TSS [ML^{-3}], *in mg·L⁻¹*, denotes the concentration of suspended solids in recharge water, and d_g [L], is the mean diameter of the filter grains. With these units, the infiltration rate, i [LT^{-1}], must be expressed *in m·d⁻¹*.

SIEGRIST & BOYLE (1987) obtained a good correlation between infiltration rate at a given time t and the cumulative loading of total biological oxygen demand, $t\text{BOD}$ [ML^{-3}]^a –defined as the carbonaceous plus the nitrogenous biochemical oxygen demand, BOD [ML^{-3}]– plus the cumulative density loading of total suspended solids, TSS [ML^{-3}], for pilot infiltration cells:

$$i = \frac{241 \exp[2.63 - 5.70(t\text{BOD}) + 41.08(\text{TSS}) - 0.048(t\text{BOD} \cdot \text{TSS})]}{1 + \exp[2.63 - 5.70(t\text{BOD}) + 41.08(\text{TSS}) - 0.048(t\text{BOD} \cdot \text{TSS})]} \quad [2.9.]$$

They insisted that the deduced relation can not be used for other sites, because the differences in specific soil, climatic conditions, infiltration surface (geometry and depth) properties, wastewater quality and application regime.

TAYLOR & JAFFÉ (1990a) published a very interesting analytical bioclogging model accounting for changes in the main parameters of the aquifer. But they previously attained an empirical correlation (TAYLOR & JAFFÉ, 1990b) that quantifies the current value of intrinsic permeability, k [L^2], relative to the initial value, k_0 [L^2], as a function of bacterial organic carbon, BOC [ML^{-3}]. This parameter is defined as the total organic carbon, TOC [ML^{-3}], minus the concentration of soluble organic carbon, SOC^b [ML^{-3}].

$$\frac{k}{k_0} = \begin{cases} \exp\{\gamma_1[\text{BOC}] + \gamma_2[\text{BOC}]^2\} & [\text{BOC}] < 0.4 \text{ mg} \cdot \text{cm}^{-3} \\ \gamma_3 & [\text{BOC}] > 0.4 \text{ mg} \cdot \text{cm}^{-3} \end{cases} \quad [2.10.]$$

where γ_1 [M^{-1}L^3], γ_2 [M^{-2}L^6] and γ_3 [L^0] are three adjustable parameters. Strictly, \mathbf{k} and \mathbf{k}_0 are tensors, but a scalar value was considered in this case (1-D vertical flow).

For recharge wells and physical clogging, OLSTHOORN (1982) obtained a semi-empirical equation that is widely used for comparison purposes, because it considers standardised values that can be easily extrapolated to particular cases:

$$i = \frac{i_0}{\sqrt{1 + \omega_0 t}}, \quad \text{where } \omega_0 \equiv \left(\frac{2}{P}\right) \left(\frac{\text{TSS} \cdot \mu_1}{k}\right) i_0^2 \quad [2.11.]$$

HUTCHINSON & RANDALL (1995) developed a useful standard graph to assess the risk of physical clogging in wells by using [1] the normalised clogging build-up as introduced by OLSTHOORN (1982) and [2] type-curves for hydraulic conductivity and the modified fouling index. As mentioned above, it is also possible to use the concentration of suspended solids instead of MFI.

^a Concentration can be expressed in several ways. The most frequent way consists in giving the mass of solute per unit volume of solution [$\text{mg} \cdot \text{L}^{-1}$], but it is also frequent to do it in $\text{mmol} \cdot \text{L}^{-1}$, $\text{meq} \cdot \text{L}^{-1}$ or in relative terms [mg solute per mg solvent]. This implies that proportionality factors must be used to transform between different formulations.

^b The soluble organic carbon, SOC, is obtained by filtration of recharge water through a $0.45 \mu\text{m}$ membrane.

2.3.2. THEORETICAL MODELS

There are numerous theoretical models in the literature too. None of them opts for an integrated approach to the problem of clogging, but focuses instead on any of the individual mechanisms. Other models deal with complicated reactive transport equations, but they ignore the changes in porosity (and consequently in intrinsic permeability) caused by the physiochemical reactions. A schematic list of models is presented below.

2.3.2.1. *Physical Clogging Models*

- **Macroscopic model by Iwasaki**

The first known and widely equation used was proposed by IWASAKI (1937). He introduced a 1-D macroscopic model to describe the behaviour of the concentration of suspended particles in the liquid, c_1^p [ML⁻³]^c, as a function of penetration length in the medium, z [L]:

$$\frac{\partial c_1^p}{\partial z} = -\lambda_0 c_1^p \quad [2.12.]$$

where λ_0 [L⁻¹] is the widely used filtration coefficient, which probably represents the most important feature of this model.

- **Macroscopic approach by Herzig et al**

HERZIG ET AL. (1970) proposed a crucial model for the time evolution of concentration of retained particles that is presented here in detail. A basic assumption is that interaction between suspended particles is neglected, which can be a considerable oversimplification if a coagulation/flocculation treatment is applied.

The starting point is the well-known advection-diffusion equation for the concentration of suspended particles under steady state flow conditions:

$$\frac{\partial}{\partial t} (c_s^p + \phi c_1^p) + q \frac{\partial c_1^p}{\partial z} - D \frac{\partial^2 c_1^p}{\partial z^2} = 0 \quad [2.13.]$$

where D [L²T⁻¹] is the diffusion coefficient; ϕ [L⁰] is porosity; and q [LT⁻¹] is Darcy's velocity. Concentrations in this model are expressed in volume of particles per unit of bulk volume. For instance, c_s^p is the volume of retained particles per unit of filter volume. In this model, the porosity changes as a result of the attachment of particles in accordance to:

$$\phi = \phi_0 - \beta_s c_s^p \quad [2.14.]$$

where ϕ_0 [L⁰] is the initial porosity of the filter and β_s [L⁰] is the inverse of the compaction factor of retained particles. In this model, β_s was estimated at 2 or 3, and accounted for the effect of imprisoning 'dead liquid' among the particles, which would affect the effective accumulated volume of particles. However, β_s is difficult to determine, since it depends on particles size and

^c Usually, the concentration of particles (p) in the liquid phase (l) is expressed in dimensionless form, i.e., in mass of particles per unit mass of the liquid (Chapter III), w_l^p [L⁰].

shape and the texture of the porous medium (HERZIG ET AL., 1970). Further, β_s cannot be considered constant, since the blocking of a pore by one or more particles does not exclude the deposition of more particles, which would modify the value of this parameter without significantly affecting the flow distribution.

After establishing the mass balance for particles, they investigated three approximations:

3rd approximation: neglecting the diffusive term in equation [2.13.].

2nd approximation: taking a constant porosity value in equation [2.13.].

1st approximation: neglecting the contribution of suspended particles to the time derivative in equation [2.13.], i.e. $\phi c_1^p \ll c_s^p$.

However, the key aspect of this work was to conceptually define the form of the kinetic equation that describes the mass transfer rate between mobile and retained particles. This was not done theoretically because the mass transfer is a function of elementary processes, but was inferred from experiments and also from the definition of attachment probabilities. The resulting kinetic equation of clogging is:

$$\frac{\partial c_s^p}{\partial t} = \lambda' c_1^p \quad [2.15.]$$

where λ' [T^{-1}] is called the clogging rate constant.

It is very interesting to remark that Iwasaki's equation is not exactly a kinetic equation, since manipulating both equation [2.12.] and [2.13.] -with the third approximation (i.e. no diffusion)- yields:

$$\frac{\partial (c_s^p + \phi c_1^p)}{\partial t} = q \lambda_0 c_1^p \quad [2.16.]$$

However, when the first approximation is justified then a kinetic equation is obtained through the use of Iwasaki's filtration coefficient,

$$\frac{\partial c_s^p}{\partial t} = q \lambda_0 c_1^p \quad [2.17.]$$

i.e. the clogging rate can be approximated as the filtration coefficient times the flow velocity.

Finally, it is worth explaining that a global clogging rate constant can be obtained if both attachment and detachment are lumped into a single parameter, whose definition is:

$$\lambda' = \lambda'_a \phi - \frac{\lambda'_d c_s^p}{c_1^p} \quad [2.18.]$$

where λ'_a [T^{-1}] is the attachment rate and λ'_d [T^{-1}] is the detachment rate. However, only the attachment term was considered in the work published by HERZIG ET AL. (1970).

- **Microscopic attachment and detachment rates**

More refined models were subsequently suggested to provide theoretical basis for the kinetics coefficients (attachment and detachment parameters). A sophisticated approach was made by YAO ET AL. (1971) in order to improve the description of the mass transfer rates by means of a

microscopic analysis. A demonstration of the power of microscopic analysis is contained in RAJAGOPALAN & TIEN (1976), who separated the attachment rate into three additive terms: Brownian diffusion, interception and gravity. By solving the trajectory equation for the motion of a particle they obtained the following relationship:

$$\lambda'_a = \frac{D_B}{d_g} \left[\frac{1}{4} A_s N_{LO}^{1/8} N_{In}^{15/8} N_{Pe} + \frac{17 \cdot 10^{-3}}{20} N_{Gr}^{1/2} N_{In}^{-2/5} N_{Pe} + A_s N_{Pe}^{1/3} \right] \quad [2.19.]$$

where $D_B [L^2T^{-1}]$ is the Brownian diffusion coefficient of the particles. $A_s [L^0]$ is a geometric factor that depends on porosity; N_{LO} , N_{In} , N_{Pe} and $N_{Gr} [L^0]$ are, respectively, the London, interception, Peclet and gravity numbers. These five numbers are defined by next equation:

$$\begin{aligned} A_s &= \frac{2(1-y^5)}{(2-3y+3y^5-2y^6)} \\ N_{LO} &= \frac{4H}{9\pi\mu_1 d_p^2 q} & N_{In} &= \frac{d_p}{d_g} \\ N_{Pe} &= \frac{d_g q}{D_B} & N_{Gr} &= \frac{d_p^2 (\rho_s - \rho_l) g}{18\mu_1 q} \end{aligned} \quad [2.20.]$$

where $y \equiv (1-\phi)^{1/3}$. $H [ML^2T^{-2}]$ is the Hamaker constant that controls the strength of London-van der Waals attractive forces; $d_p [L]$ is the mean diameter size of the suspended particles; ρ_s and $\rho_l [ML^{-3}]$ are, respectively, the density of particles and liquid; and $g [LT^{-2}]$ is the gravity acceleration modulus. The model assumed that suspended particles and filter grains were spherical. This, together with the use of attractive electrokinetic forces, was questioned by several authors (TOBIASSON & O'MELIA, 1988; ELIMELICH & O'MELIA, 1990).

An important characteristic of clogging is that retained particles can act as collectors as well, behaving like soil grains. This process is termed 'ripening', and was first included by O'MELIA & ALI (1978) for a mono-disperse solution. They modified the removal efficiency to incorporate the effects of ripening, that is, the new removal efficiency being equal to the sum of the former efficiency plus the collected particles efficiency. This model also experienced several modifications, like the one proposed by TARE & VENKOBACHAR (1985). In their approach, surface coverage changes during the filtration process and there are important variations of the concentration of retained particles with depth.

Other modifications focus on the effects of heterodisperse solutions (VIGNESWARAN & AIM, 1983; DARBBY ET AL., 1992) and on heterodisperse solutions plus breakthrough -that is, detachment- (VIGNESWARAN & CHANG, 1986; VIGNESWARAN & TULACHAN, 1988). According to CLEASBY (1990), filtration is a dynamic process consisting of a ripening stage, a period of steady operation and a breakthrough stage. An interesting qualitative review, grouping different analytical models looking at their main assumptions, is done by MORAN ET AL. (1993).

- **Modifications of Herzig et al. model**

There are various models that have been successfully used to interpret laboratory data. For instance, RAJAGOPALAN & CHU (1982) used an analogous model -equations [2.13.], [2.15.] and [2.18.]- but they: (1) explicitly included detachment and (2) related the attachment and

detachment rates to the physical clogging mechanism. The formal expression of this model is as follows:

$$\begin{aligned} \frac{\partial c_l^p}{\partial t} + u_m \frac{\partial c_l^p}{\partial z} + \frac{\rho_s a'_s (1-\phi)}{\phi} \frac{\partial c_s^p}{\partial t} &= 0 \\ \frac{\partial c_s^p}{\partial t} &= \lambda'_a c_l^p - \lambda'_d c_s^p \end{aligned} \quad [2.21.]$$

where u_m [LT^{-1}] is the water velocity and a'_s [$M^{-1}L^2$] is area available for adsorption per unit mass of grains. In equation [2.19.], c_l^p is expressed as number of suspended particles in the liquid per unit volume of suspension, whilst c_s^p represents the number of retained particles per unit area of grains. This is why the attachment and detachment rates, λ'_a and λ'_d , are not identical to the ones appearing in equation [2.18.].

According to empirical observations, this model tended to underestimate attachment when suspended solids and grains had the same charge, that is, when repulsive electric forces became relevant. In fact, particles already adsorbed on grains begin to influence the flow very soon: they act at very low coverage percentages (2% to 4%), due to geometrical effects and not to the surface charge. The model proved to be quite accurate when suspended particles and grains had opposite charges.

A similar 1-D macroscopic model was formulated by ADIN & REBHUN (1987), including retention and re-mobilisation of suspended particles, by means of a simplified transport equation without diffusion:

$$\begin{aligned} q \frac{\partial c_l^p}{\partial x} + \frac{\partial c_s^p}{\partial t} &= 0 \\ \frac{\partial c_s^p}{\partial t} &= \lambda_0 q c_l^p (F - c_s^p) - \lambda'_d c_s^p J \end{aligned} \quad [2.22.]$$

where F [L^0] is the filter capacity, which determines the maximum retention potential of the medium; and J [L^0] is the hydraulic gradient.

This model is equivalent to Herzig's model without diffusion and using the first approximation, i.e. $\phi c_l^p \ll c_s^p$. The main difference lies in the form of the attachment and detachment terms. The accumulation term is based on physical considerations, although the concept of the filter capacity may be questionable (CLEASBY, 1984). The detachment term is also a subject of controversy; some authors argue that it is not relevant at all (IVES, 1969, 1973), whilst it is included by others (MINTZ, 1964; SHEKHTMAN, 1961). Shear forces increase as clogging develops, due to a decrease in porosity and the corresponding augment in filtration velocity (GHOSH ET AL., 1985). A linear dependence of time evolution of the concentration of retained particles on the concentration of retained particles itself was suggested by (SAKTHIVADIVEL & IRMAY (1966) and MINTZ (1964). Equation [2.22.] accounts for the influence of hydraulic gradient on the detachment rate.

GOVINDARAJU & REDDI (1994) proposed a variation on the last model that did not use the concentration of retained particles, c_s^p . Instead, they worked with the concentration of suspended particles alone, and introduced two new parameters: the detachability coefficient, ξ [L^0], and the critical shear stress, τ_{cr} [$ML^{-1}T^{-2}$]. The former influences the sink/source term, whilst the latter

establishes a limitation between attachment and detachment based on hydraulic conditions. In sum, attachment and detachment depend on the hydraulic properties and status of the system.

- **Purely Hydraulic Models**

Various authors have searched for more elemental relationships based on hydraulic considerations. Only three of these models are briefly described here.

IVES & PIENVICHITR (1965) proposed a model whose basic assumption was that the porous medium could be represented by a bundle of tortuous, non-interconnected capillary tubes of varying radii. Their predicted hydraulic conductivity reduction can be expressed as:

$$\frac{K}{K_0} = \left(\frac{\phi - \phi_0}{\phi_0} \right)^{3 - 2\alpha_{IP}} = \left(\frac{\beta_s c_s^p}{\phi_0} \right)^{3 - 2\alpha_{IP}} \quad [2.23.]$$

where K and K_0 [LT^{-1}] are the current and initial value of hydraulic conductivity, respectively (strictly, \mathbf{K} is a tensor); β_s [L^0] was defined in the model of HERZIG ET AL. (1970) and α_{IP} [L^0] is a variable positive exponent that depends on how the diameter of the capillaries is assumed to vary with time as a result of clogging. A value of $\alpha_{IP}=1.25$ (net exponent of 0.5) is equivalent to assuming uniform coating of the tubes.

A generalisation of equation [2.23.] was implemented by TIEN ET AL. (1979):

$$\frac{K}{K_0} = (1 - c_s^p)^3 \left[1 + \frac{\phi_0 c_s^p}{1 - \phi_0} \right]^{-4/3} \quad [2.24.]$$

OSEI-BONSU (1996) proposed a mathematical model for physical clogging based on experimental results obtained under confined radial-flow conditions in a 90° laboratory-scale segment. According to this model, the ratio of hydraulic conductivity reduction with time can be written as a function of time and two parameters, α_{OB} and ω_{OB} (OSEI-BONSU & ARMSTRONG, in preparation):

$$\left[1 - \left(\frac{K}{K_0} \right)^{1/3} \right] = (\alpha_{OB1} t)^{\alpha_{OB2}} \quad [2.25.]$$

where α_{OB1} [T^{-1}] is a proportionality factor; and α_{OB2} [L^0] is a parameter determined by the dominant clogging mechanism. It is 0.5 for blocking filtration and 1.0 for deep bed filtration. The model is based on the assumption that the changes in hydraulic conductivity caused by the deposition of suspended particles can be assimilated to a series of steady-state changes of the hydraulic gradient. One important finding of OSEI-BONSU was that, for the same mass flux, the lower the concentrations of suspended solids the higher the rate of clogging.

2.3.2.2. **Biological Clogging Models**

Three types of bioclogging models exist: (1) macroscopic models, (2) models based on the concept of micro-colonies, and (3) biofilm models. Although the conceptual framework of each group may look different, BAVEYE & VALOCCHI (1989). have shown that macroscopic transport equations for each of the groups are formally identical if the micro-colonies and the biofilms are fully penetrated.

The three approaches are described below by means of representative examples found in the literature.

(i) *Strictly macroscopic models*

The best example of this type of models is provided by OKUBO & MATSUMOTO (1979). Their model could be applied to other clogging sources, given the fact that only hydraulic considerations are made. Unlike other biological models, they did not implement bacterial metabolism. Instead, they considered the porous medium to be formed by a bundle of capillary tubes of equal initial diameter, d_{t0} [L], embedded in the soil. According to the HAGEN-POUSEUILLE equation, the initial specific discharge:

$$Q_0 = -N_t \frac{\pi d_{t0}^4 \rho_1 g}{128 \mu_1} J \quad [2.26.]$$

where Q_0 [$L^3 T^{-1}$] is the discharge; N_t [L^{-2}] is the number of tubes per unit area and J [L^0] is the hydraulic gradient.

At time t , the discharge, Q , will be defined by an analogous equation but the diameter of the tubes will be reduced due to bioclogging. The first assumption of the model was that the reduction in diameter was uniform. Under the second assumption, the volume decrease per unit length of tube is proportional to the cumulative discharge through an adjustable parameter:

$$\frac{\partial V_p}{\partial z} = \frac{\pi}{4} (d_{t0}^2 - d_t^2) = \alpha_{OM1} V \quad [2.27.]$$

where V_p [L^3] is the volume of the void space (pores); d_t [L] is the reduced diameter of the tubes; α_{OM1} [L] is a fitting parameter; and V [L] is the cumulative discharge.

After some algebraic manipulations of the previous equations, it is possible to write a more compact expression for the discharge affected by bioclogging:

$$Q = \frac{\partial V}{\partial t} = Q_0 (1 - \alpha_{OM2} V) \quad [2.28.a]$$

where

$$\alpha_{OM2} \equiv \frac{4 \alpha_{OM1}}{\pi d_{t0}^2} \quad [2.28.b]$$

After integration, with the initial condition that $V=0$ at $t=0$, it is finally derived that:

$$V = \frac{Q_0 t}{1 + \alpha_{OM2} Q_0 t} \quad [2.29.]$$

VIGNESWARAN & SUAZO (1987) used a modification of equation [2.29.] to predict bioclogging at different infiltration rates. Predictions were based in laboratory experiments that served to obtain the empirical coefficient, α_{OM1} (or α_{OM1}). Results obtained showed a good agreement with measured data. However, VANDEVIVERE ET AL. (1995) have demonstrated that the model defined by OKUBO & MATSUMOTO is just a special case of the model proposed by IVES & PIENVICHITR (1965) when $\alpha_{IP}=0.5$ in equation [2.23.].

(ii) Models based on Micro-colonies

Another approach consists in assuming that bacteria grow in discrete micro-colonies that are attached to the porous medium. Micro-colonies are supposed to consist of isolated cylinders of radius r_c [L], height b_c [L], mass m_c [M], and density ρ_c [ML⁻³]. The volume of a micro-colony, V_c [L³], can thus be written as $V_c = \pi r_c^2 b_c$. The colony density is defined by N_c [L⁻³]. Micro-colonies may be separated from the water phase by a diffuse layer of thickness δ_c [L].

In accordance with previous investigations (RITTMAN & MCCARTY, 1980; BENEFIELD & MOLZ, 1985), MOLZ ET AL. (1986) developed a model for aerobic heterotrophic bacteria. This 1-D model is described by the following set of equations:

$$Y R^s = \mu_{\max} \rho_c V_c \left[\frac{c_c^s}{g^s + c_c^s} \right] \left[\frac{c_c^o}{g^o + c_c^o} \right] \quad [2.30.a]$$

$$r_o = f_{\text{syn}}^o Y R^s + f_{\text{en}}^o \mu_{\text{dec}} m_c \left[\frac{c_c^o}{g^o + c_c^o} \right] \quad [2.30.b]$$

$$D_s \left(\frac{c_1^s - c_c^s}{\delta_c} \right) \pi r_c^2 = R^s \quad [2.30.c]$$

$$D_o \left(\frac{c_1^o - c_c^o}{\delta_c} \right) \pi r_c^2 = R^o \quad [2.30.d]$$

$$\frac{\partial}{\partial t} \{ \phi c_1^s + c_s^s (a_s - N_c \pi r_c^2) \} = - \frac{\partial}{\partial x} \left(\phi u_m c_1^s - \phi D_s \frac{\partial c_1^s}{\partial x} \right) - D_s \left(\frac{c_1^s - c_c^s}{\delta} \right) N_c \pi r_c^2 \quad [2.30.e]$$

$$\frac{\partial}{\partial t} \{ \phi c_1^o + c_s^o (a_s - N_c \pi r_c^2) \} = - \frac{\partial}{\partial x} \left(\phi u_m c_1^o - \phi D_o \frac{\partial c_1^o}{\partial x} \right) - D_o \left(\frac{c_1^o - c_c^o}{\delta} \right) N_c \pi r_c^2 \quad [2.30.f]$$

- Equation [2.30.a] is a modification of MONOD kinetics for the utilisation of nutrients (substrate). Y [L⁰] is the yield coefficient that (stoichiometrically) relates the growth of microorganisms to the utilisation of substrate; R^s [MT⁻¹] is the rate of utilisation of the substrate; μ_{\max} [T⁻¹] is the maximum growth rate MONOD's kinetics; c_c^s and c_c^o [ML⁻³] are the substrate and oxygen concentrations within the colony, respectively; and g^s and g^o [ML⁻³] are the half-saturation constants for substrate and oxygen.
- Equation [2.30.b] incorporates PIRT kinetics for oxygen consumption by the micro-colonies. R^o [MT⁻¹] is the rate of utilisation of oxygen; f_{syn}^o and f_{en}^o [L⁰] account for fraction of oxygen used for synthesis and energy, respectively; μ_{dec} [T⁻¹] is the microbial decay coefficient.
- Equations [2.30.c] and [2.30.d] refer to diffusion of substrate and oxygen, respectively, through the diffuse layer. D_s and D_o [L²T⁻¹] are diffusive parameters for the substrate and oxygen; c_1^s and c_1^o [ML⁻³] are the substrate and oxygen concentration in water, respectively.
- Equations [2.30.e] and [2.30.f] account for the transport of substrate and oxygen within the aquifer formation. c_s^s and c_s^o [ML⁻²] are the mass of adsorbed substrate and oxygen per unit area; a_s [L⁻¹] is the specific reactive surface of the matrix.

A Freundlich isotherm is employed to relate the adsorbed mass of substrate or oxygen concentration in water. After some considerations about the net biomass production rate for a colony and for the total volume, they came to a final equation that, together with equation [2.30.a] constitutes the proposed model:

$$\frac{\partial N_c}{\partial t} = \frac{1}{m_c} (Y R^s - \mu_{dec} m_c) N_c \quad [2.31.]$$

To adopt equation [2.31.], a constant average colony size and constant mass was assumed.

(iii) *Biofilm Models*

The third approach includes a new phase, the biofilm, composed by bacteria and a matrix of extra-cellular material, which forms a continuum along the porous medium. The biofilm is mainly constituted by water, although interactions with the liquid phase must be quantified too. The basic hypotheses of TAYLOR & JAFFÉ (1990a) open pore biofilm model, whose basic hypotheses are:

- Rigid and saturated porous medium that is chemically inert.
- There is a unique limiting substrate that cannot sorb onto the porous medium.
- MONOD kinetics apply, and bacterial decay follows a first order law.
- The aquifer parameters, such as porosity, permeability and dispersivity, change as a result of biomass attachment and detachment; then, biofilm thickness controls the variation of those parameters.
- Mass balance equations are established for biomass, waster and the substrate. Transport equations include advection, diffusion, production and decay.

The model is defined by the following equations:

$$\frac{\partial}{\partial t} (\phi c_1^b) = \nabla(\phi \mathbf{D} \nabla c_1^b) - \nabla(\mathbf{q} c_1^b) + \phi \rho_l R_1^b + R_{she} - R_{det} \quad [2.32.a]$$

$$\frac{\partial}{\partial t} (w_b^b \rho_b) = w_b^b \rho_b R_b^b + R_{det} - R_{she} \quad [2.32.b]$$

$$\frac{\partial}{\partial t} (\phi c_1^s) = \nabla(\phi \mathbf{D} \nabla c_1^s) - \nabla(\mathbf{q} c_1^s) + \phi \rho_l (R_{lb}^s) \quad [2.32.c]$$

- Equation [2.32.a] is the mass balance for the biomass in the liquid, whose concentration is defined by c_1^b [ML⁻³]. R_1^b [T⁻¹] the net rate of biomass production in the liquid phase, which is described through MONOD's equation and a first-order decay relationship; R_{she} [T⁻¹] is the shear rate of biomass from the biofilm due to fluid mechanical forces; and R_{det} [T⁻¹] is the rate of deposition of biomass from the liquid to the biofilm or the solid phase. Exact expressions for the shear and deposition rates are based in previous developments of different authors. A classical first-order dependency on the concentration of biomass in the liquid was adopted for R_{det} (like HERZIG ET AL., 1970), whilst the shear term, R_{she} , was taken from SPEITEL & DIGIANO (1987).
- Equation [2.32.b] is the mass balance for the biofilm phase (the biomass occurs in a continuous film, the biofilm). The volume fraction of biofilm phase is denoted by w_b^b [L⁰]. The net rate of biomass production in the biofilm, R_b^b [T⁻¹], is expressed by integration of MONOD's equation over the biofilm thickness, L_b [L].
- Equation [2.32.c] represents the mass balance for substrate in the liquid. In analogy to the previous equations, R_{lb}^s [T⁻¹] is sum of (1) the rate of substrate utilisation by the biomass in the liquid phase and (2) the transfer of substrate from the liquid to the liquid phase by diffusion across the boundary. Explicit relationships can be consulted in TAYLOR & JAFFÉ (1990a).

A key aspect of this model is the relationship between porous media parameters and biological growth. This is a must for any clogging model, irrespective of the clogging mechanism. Within the

group of conduit flow models, two basic approaches can be used to describe changes in porous media due to bioclogging:

1. **Geometrical models** do not consider the size distribution of pores in the medium. The KOZENY-CARMAN model (KOZENY, 1927; CARMAN, 1937) exemplifies this approach:

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0} \right)^3 \left(\frac{a_{s0}}{a_s} \right)^2 \quad [2.33.]$$

where a_s and a_{s0} [L^{-1}] are the current and initial values of the surface area of the porous medium (internal surface area per unit bulk volume), respectively.

Equations that relate the changes in porous media parameters and biofilm coating of the grains are based on DEB (1969). In case of cubic packing, the initial porosity and surface area of the medium can be written as:

$$\begin{aligned} \phi_0 &= 1 - \frac{\pi}{6} \\ a_s &= \frac{\pi}{d_g} \end{aligned} \quad [2.34.]$$

Using these concepts, TAYLOR ET AL. (1990) arrived at the following mathematical expressions for the porosity and surface area evolution of a porous medium subject to bioclogging –for cubic packing–:

$$\begin{aligned} \phi &= 1 + \pi \left[\frac{1}{3} \left(\frac{2L_b}{d_g} \right)^3 + \frac{1}{4} \left(\frac{2L_b}{d_g} \right)^2 - \frac{1}{2} \left(\frac{2L_b}{d_g} \right) - \frac{1}{6} \right] \\ a_s &= \pi \left[1 - \left(\frac{2L_b}{d_g} \right) - 2 \left(\frac{2L_b}{d_g} \right)^2 \right] \end{aligned} \quad [2.35.]$$

whilst KOZENY-CARMAN equation fully describes the time evolution of hydraulic conductivity due to bioclogging.

2. **Statistical models** consider the random nature of the interconnectedness of the pores. The cut-and-random-rejoin-type model by Mualem (1976) proposes the following equations for porosity, surface area and intrinsic permeability of the medium in the absence of clogging:

$$\begin{aligned} \phi &= \int_{r_{\min}}^{r_{\max}} f(r) dr \\ a_s &= 2 \int_{r_{\min}}^{r_{\max}} \frac{f(r)}{r} dr \\ k &= \frac{\kappa \phi^\gamma}{8} \left[\int_{r_{\min}}^{r_{\max}} r f(r) dr \right]^2 \end{aligned} \quad [2.36.]$$

where $f(r)$ is the pore size distribution of the medium, which is defined by $d\theta \equiv f(r)dr$, and $\theta(r)$ is the unsaturated moisture content when all pores with radius smaller than r are filled; r_{\min} and r_{\max}

[L] are, respectively, the minimum and maximum pore radius; κ [L⁰] and γ [L⁰] are two constants. MUALEM (1976) suggested that $\gamma=0.5$.

TAYLOR ET AL. (1990) particularised this formulation by using a power function to characterise the pore size distribution. After applying the biofilm concept to MUALEM's model, the expressions for biofilm-affected porous media parameters can be obtained by modifying equation [2.36.]. The exact expressions are available in TAYLOR ET AL. (1990).

(iv) Performance of Bioclogging Models

VANDEVIVERE ET AL. (1995) compared three types of models: (1) the hydraulic model developed by IVES & PIENVICHITR (1965), (2) the KOZENY-CARMAN model of TAYLOR ET AL. (1990) model, and (3) the MUALEM model of TAYLOR ET AL. (1990). Despite the different conceptual frameworks of these models, all of them achieved reasonable results for coarse-textured materials. However, the models have a tendency to underpredict the hydraulic conductivity reduction in fine-textured materials by orders of magnitude.

Since the analysed models assumed a complete coverage of the grains (continuous biofilm), VANDEVIVERE ET AL. (1995) argued that a simplistic model where biomass was distributed in plugs would provide better predictions. This simple model is described by equation [2.37]:

$$\frac{K}{K_{\text{plug}}} = \frac{(\phi_0)^2}{\phi_0 - \phi} \quad [2.37.]$$

where K_{plug} [LT⁻¹] is the hydraulic conductivity of the plugs, which accounts for all the head loss within the capillaries.

This model has severe limitations (too simplistic geometry, ignoring the kinetics of plugs formation, not incorporating bacterial mechanisms), but can give satisfactory results for fine-textured media. In order to do so, it is necessary to propose a value for the ratio K_{plug}/K , i.e. to provide an estimate for the reduction of conductivity. Values of 10⁻³ to 10⁻⁴ would be acceptable, in principle. However, it is clear that some estimates have to be done before applying the model.

More recently, HOLM (1999) applied a statistical model to data from laboratory columns. The model had difficulties in predicting the response to clogging and to obtain a consistent set of model parameters (they had to be varied with varying input conditions). However, coupling empirical relationships with detailed numerical modelling seems to be a promising approach to complicated biological reactions and biofilm-induced clogging.

2.3.2.3. Chemical Clogging Models

Recent developments in reactive transport analytical and numerical (especially finite differences or finite elements) models are outstanding. However, reactive transport models have not been applied to clogging problems. This is probably due to the amount of data necessary to verify the conceptual model and the difficulty to quantify changes in aquifer parameters and to relate them to pressure (or head) build-up.

Instead of trying to describe those models, which can be found elsewhere (LASAGA, 1981; STEEFEL, 1992; SAALTINK ET AL., 1997), a specific model for bacteria-catalysed iron precipitation observed in laboratory experiments (OMURA ET AL., 1991) is briefly commented. Their initial hypotheses are:

- Iron is the only limiting substrate. The oxygen concentration in infiltrating water is high enough so as not to limit ferrous iron (Fe^{+2}) oxidation in accordance to MONOD's kinetics.
- Only the attached cells (bacteria fixed on the medium walls) are important as concerns oxidation and growth. Mobile bacteria are not considered in the model.
- Cells detached from the support medium are instantly transferred to the liquid phase.
- The medium is assumed to be formed by three phases: the support medium (or matrix), the stagnant liquid film, whose width is defined by δ_l [L], and the liquid.

The model performs mass balances for:

- Fe^{+2} in the support medium (matrix), which is formed by spherical grains of radius R_g [L]. Equation [2.38.a] describes this balance ($0 < r \leq R_g$).
- Fe^{+2} in the stagnant liquid film ($R_g \leq r \leq R_g + \delta_l$), Equation [2.38.b].
- Fe^{+2} in the bulk liquid, equation [2.38.c].
- Attached bacteria in the support medium, equation [2.38.d].

$$\frac{\partial c_s^s}{\partial t} = D \left(\frac{\partial^2 c_s^s}{\partial r^2} + \frac{2}{r} \frac{\partial c_s^s}{\partial r} \right) - \frac{N_s^b \mu_{\max} c_s^s}{\phi g^s + c_s^s} \quad [2.38.a]$$

$$\frac{\partial c_w^s}{\partial t} = D \left(\frac{\partial^2 c_w^s}{\partial r^2} + \frac{2}{r} \frac{\partial c_w^s}{\partial r} \right) \quad [2.38.b]$$

$$\frac{\partial c_l^s}{\partial t} = \frac{Q}{V_R \phi} [c_l^s|_{in} - c_l^s] - 3 \left(\frac{1-\phi}{\phi} \right) \frac{(0.5d_g + \delta_w)^2}{d_g^3/8} D \frac{\partial c_l^s}{\partial r} \Big|_{R_g + \delta_w} \quad [2.38.c]$$

$$\frac{\partial N_s^b}{\partial t} = N_s^b Y \frac{\mu_{\max} c_s^s}{g^s + c_s^s} - (\mu_{\text{dec}} + R_{\text{she}}) N_s^b \quad [2.38.d]$$

where c_s^s [ML^{-3}] is the Fe^{+2} concentration in the support medium; c_w^s [ML^{-3}] is the Fe^{+2} concentration in the stagnant liquid film; c_l^s [ML^{-3}] is the Fe^{+2} concentration in the liquid, with subscript *in* referring to the input concentration; N_s^b [L^{-3}] is the attached cell number in the support medium; V_R [L^3] is the reactor volume; and R_{she} [T^{-1}] was defined in the model by TAYLOR & JAFFÉ (1990a).

The problem resides in how to determine the three kinetics parameters: the yield coefficient, Y [L^0], the die-off rate, μ_{dec} [T^{-1}] and the detachment rate, R_{she} [T^{-1}]. Apart from solving the system of equations [2.38.a] through [2.38.d], OMURA ET AL. (1991) made a balance for mobile bacteria in the column (reactor) and another balance for attached bacteria in the column, in steady state, with the aim of finding a relationship among those parameters. The resulting equation is as follows:

$$\frac{Q N_l^b}{(1-\phi) V_R N_s^{b*}} = \frac{[c_l^s|_{in} - c_l^s]}{(1-\phi) V_R N_s^{b*}} Q Y - \mu_{\text{dec}} \quad [2.39.]$$

where N_s^{b*} [L^{-3}] is the attached cell number in the support medium at steady state.

Equation [2.39.] can be used to determine the values of Y and μ_{dec} after substituting for the empirical results, so that they are obtained from the slope and the intercept of a straight line, respectively. Then, R_s can be deduced from the transient mass balance for mobile bacteria in the column, which is not shown here.

OMURA ET AL. (1991) concluded that pH should be kept below 2 in order to avoid clogging by ferric hydroxide. Also, they found that temperature variations did not prove to be very important. It is evident that such a requirement is unfeasible from a practical perspective, but it helps in understanding the clogging potential of chemical compounds by means of biotic (bacterially-mediated) and abiotic reactions.

2.3.2.4. Compaction

Compaction is an uncommon situation, which takes place when water height is too big and causes the clogging layer to compress. Therefore, compaction does not refer to the aquifer formation itself. The work by PERSON ET AL. (1996) can be consulted for further information. Basically, deformation of porous media is due to the application of external forces, \mathbf{F} [$\text{ML}^{-2}\text{T}^{-2}$], which splits into:

- (1) internal stress, given by the divergence of the tensor of porous medium stress, $-\nabla\boldsymbol{\sigma}$
- (2) inertial forces, which are usually negligible for slow rates of deformation.

When small elastic strains are applicable to macroscopically continuous porous medium:

$$\mathbf{F} \approx -\nabla\boldsymbol{\sigma} \quad [2.40.]$$

A constitutive equation is required to relate the strain tensor, $\boldsymbol{\varepsilon}$ [L], and the stress tensor, $\boldsymbol{\sigma}$ [$\text{ML}^{-1}\text{T}^{-2}$]. A classical example is the relationship introduced by BIOT (1941):

$$\boldsymbol{\varepsilon} = \frac{1}{E} \left[(1 + \nu_{bi}) \boldsymbol{\sigma} - \nu_{bi} \text{Tr}\{\boldsymbol{\sigma}\} \boldsymbol{\delta}_{ij} \right] + \frac{P}{3H_{bi}} \boldsymbol{\delta}_{ij} \quad [2.41.]$$

where ν_{bi} [L^0] and H_{bi} [$\text{ML}^{-2}\text{T}^{-2}$] are Poisson's modulus and a bulk modulus of the porous medium .

Finally, if the resulting displacement velocity, \mathbf{u} , is small, then another equation which links displacement and the strain rate tensor is obtained:

$$\boldsymbol{\varepsilon} = \nabla\mathbf{u} \quad [2.42.]$$

This displacement of the porous medium with regard to a fixed reference system must be included when Darcy's law is applied, because this fundamental law was originally derived for water flow velocity referred to a fixed porous medium.

2.3.2.5. New Comprehensive Approaches

As a result of a 3-years period European Union Project on Artificial Recharge, two new clogging codes were developed: CLOG (PÉREZ-PARICIO & CARRERA 1998a; PÉREZ-PARICIO ET AL., 1998; PÉREZ-PARICIO & CARRERA, 1999b) and MIKE-SHE SC (VON CHRISTIERSON, 1999). The former is the object of this thesis, so that will be exhaustively described in the following chapters. The mathematical formulation of the latter is not presented here, but a qualitative description is provided. Table 2.6. collects the essential features of both programs.

CLOG is a sphere-type model that can account for attachment and detachment of suspended particles, bacterial growth on the porous matrix and precipitation/dissolution of minerals. Multiphase flow, mechanical compaction and heat transport are also considered by the model. CLOG was generated after linking two existing codes, CODE-BRIGHT (OLIVELLA &

GARCÍA-MOLINA, 1996) and RETRASO (SAALTINK ET AL., 1997), together with the implementation of specific clogging modules (PÉREZ-PARICIO ET AL., 1998).

MIKE-SHE SC is a cut-and-random-rejoin-type (statistical) model that was implemented by adding new modules to the MIKE-SHE system. MIKE-SHE SC is a soil-clogging model describing microbial growth and transport of limiting substrates and biomass in porous media. The model is a new implementation to the existing hydrological modelling system MIKE-SHE, developed at the Danish Hydraulic Institute (Denmark). Aside from several utility programs and add-on modules MIKE-SHE comprises two models: a flow model describing integrated water flow and a model for integrated, multi- component, advective-dispersive conservative and reactive transport (VON CHRISTIERSON, 1999).

Table 2.6. Some capabilities of the new codes CLOG and MIKE-SHE.

Both codes work with mean diameter sizes of particles and grains, but there are plans to improve this treatment in the future.

Aspect \ CODE		CLOG	MIKE-SHE
3-D		✓	✓
Mesh		Finite elements	Finite differences
Clogging	Physical	✓	✓
	Biological	✓	✓
	Chemical	✓	-
	Compaction	✓	-
Reactive transport		✓	✓
Kinetics of bacterial growth		Monod	First order
Bacterial transport		-	✓
Unsaturated flow		✓	Under completion
Temperature		✓	-
Numerical solution		Direct substitution approach (DSA)	Sequential non-iterative Approach (SNIA)

MIKE-SHE SC clogging model belongs to a family of so-called two-compartment models developed in recent years by TAYLOR & JAFFÉ (1990a), ZYSSET ET AL. (1994), CLEMENT ET AL. (1996) and HOLM (1999). The model basically consists of one compartment that provides a description of the clogging processes: transport of bacteria and limiting nutrients, bacterial growth/decay and detachment/attachment of biomass. Such processes are closely coupled to a second compartment, which translates the biomass accumulation into soil permeability reductions.

At present, MIKE-SHE SC is limited to describing biogrowth and decay processes and sedimentation/detachment of organic matter. Thus, the model does not include all biological, physical and chemical processes that may cause soil clogging, such as mineral precipitation, air bubble release or soil compaction of the clogging layer. Temperature variations have not been included either in the model at this stage. The model largely follows the work of CLEMENT ET AL. (1996), who derived an empirical formula that relates biomass concentrations to the hydraulic conductivity. This model, which is based on a macroscopic approach and thus makes no

assumptions on the biomass distribution, is used in MIKE-SHE SC for relating biomass concentrations to permeability reductions. The processes of growth/decay and sedimentation/detachment are described by existing add-on modules in the MIKE-SHE modelling system. Bacterial growth is solved by the MIKE-SHE BM module using a simple first-order expression. Sedimentation, detachment and decay of biomass are solved by the sorption-degradation module MIKE-SHE SD through kinetic first-order expressions.

The existing sorption formulation has been modified to include a fully kinetic isotherm for describing sedimentation and detachment of biomass based on a model proposed by ADIN & REBHUN (1987), which includes the effects of shear forces. The system of equations describing clogging is solved for the saturated zone and partly for the unsaturated zone. The biological model in the unsaturated zone was under development.