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Application of physical clogging models to Managed Aquifer Recharge: a review of modelling approaches from engineering fields

Applicazione dei modelli di clogging fisico agli impianti di ricarica della falda in condizioni controllate: una revisione degli approcci modellistici da diversi settori ingegneristici

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Riassunto

I siti di ricarica della falda in condizioni controllate (MAR – *Managed Aquifer Recharge*) presentano il persistente problema dei fenomeni di intasamento (*clogging*). Il *clogging* può essere causato da processi di tipo fisico, biologico, chimico e meccanico, con il *clogging* di tipo fisico riconosciuto come il fenomeno predominante. L'intrusione e deposizione di materiale fine durante l'intervento di ricarica compromettono le proprietà idrauliche di infiltrazione del suolo, riducendo la capacità di infiltrazione del sito nel corso degli anni di attività: devono quindi essere previste delle operazioni di manutenzione nel tempo, al fine di ripristinare i tassi di infiltrazione iniziali. Per questi motivi, la valutazione del rischio di *clogging* può agevolare l'identificazione delle vulnerabilità del sito e rendere più efficace la progettazione dell'impianto MAR. I modelli numerici sono essenziali per replicare i processi fisici e simulare la riduzione dei tassi di infiltrazione. Finora, nella letteratura esistente per le tecniche MAR, non si dispone di strumenti previsionali per la valutazione del rischio in questione. Lo scopo di questo studio è quello di analizzare e riorganizzare i modelli numerici per il *clogging* fisico, provenienti da diversi settori dell'ingegneria che si occupano di infiltrazione in sistemi naturali eterogenei. Gli approcci modellistici sono illustrati in questa rassegna della letteratura, partendo dalle ipotesi di base e dall'elaborazione concettuale del volume del suolo e del materiale fine trasportato. I principali processi sono individuati dai molteplici studi e riorganizzati confrontando sistematicamente le equazioni matematiche di rilievo. La capacità predittiva dei modelli numerici è valutata considerandone l'adattabilità ad altri siti, seguono poi limitazioni e raccomandazioni per l'applicazione agli impianti di ricarica. Infine, vengono fornite prospettive per la valutazione del rischio di *clogging* tramite la modellazione e la caratterizzazione del sito. Lo strumento previsionale può essere un sistema di supporto alle decisioni durante la progettazione degli impianti MAR, favorendo strategie economicamente vantaggiose per ridurre il rischio di intasamento fisico.

Abstract

Managed Aquifer Recharge (MAR) sites suffer from the long-lasting problem of clogging. The causes of clogging are physical, biological, chemical and mechanical processes and their complex interaction, with physical clogging being recognised as the predominant process. The intrusion and deposition of particles during water recharge affect the hydraulic properties of the infiltration surface, resulting in a decline in the infiltration capacity of the site over the operating years. Cleaning operations are necessary to restore the original infiltration rates. For this purpose, assessing the risk of clogging can determine the site's vulnerability and improve the scheme's design. Numerical models are essential to replicate physical clogging processes and predict the decline in infiltration rates. So far, predictive tools for physical clogging assessment have been missing in MAR literature. Hence, the purpose of this study is to analyse and reorganise physical clogging models from applied engineering fields dealing with water infiltration in natural heterogeneous systems. The modelling approaches are illustrated, starting from the main assumptions and conceptualisation of the soil volume and intruding particles. The individual processes are untangled from the multiple studies and reorganised in a systematic comparison of mathematical equations relevant to MAR applications. The numerical models' predictive power is evaluated for transferability, following limitations and recommendations for a process-based model applicable to surface spreading schemes. Finally, perspectives are given for clogging risk assessment at MAR sites from modelling and site characterisation. The predictive tool could assist decision-makers in planning the MAR site by implementing cost-effective strategies to lower the risk of physical clogging.

Introduction

The reduction in recharged volumes due to clogging compromises the functionality of MAR sites (Bouwer, 2002; Dillon et al., 2022; Zhang et al., 2020). Several studies in the MAR literature suggest that physical clogging is the primary process, followed by mechanical, biological and chemical processes (Dillon et al., 1994; Pavelic et al., 2011; Rinck-Pfeiffer et al., 2000). Although the individual clogging mechanisms can occur simultaneously, this study focuses on the physical processes as main contributor to clogging. During water recharge, fine-grained sediments are transported by the source water or can originate from the soil formation itself (Hutchison et al., 2013; Martin, 2013; Racz et al., 2012). The downward movement and retention of particles in soil pores, block the water flow and lead to a pressure drop through the clogged soil (Herzig et al., 1970; Khilar and Fogler, 1998). These phenomena impact the drainage properties of the site, which entails a loss in the performance of the infiltration system.

Studies have documented observations of physical clogging directly at MAR schemes (Escalante, 2013; Martin, 2013; Pavelic et al., 2007; Rinck-Pfeiffer et al., 2000). Soil column and field experiments have been undertaken to understand relevant mechanisms in the clogging formation (Du et al., 2018; Duryea, 1996; Fichtner et al., 2019; Mays & Martin, 2013; Pavelic et al., 2011; Sallwey et al., 2019; Zou et al., 2019). The effect of clogging has been integrated into numerical simulation through time-varying parameters calibrated from the field or experimental observations (Glass et al., 2020; Majumdar et al., 2008). The comprehensive numerical code CLOG of Pérez Paricio (2001) simulates the individual clogging processes, however, kinetic parameters require further calibration for application. The modified fouling index (MFI) (Schippers & Verdouw, 1980) has been related to the rate of physical clogging in recharge wells in the work of Buik & Willemsen (2002). Although the predicted clogging rate depends on the infiltration rate on the borehole wall, suspended solids and aquifer characteristics, Maliva (2020) reports that the relationship cannot predict whether or when clogging will occur, and it works only between backflushing events. There have not been progresses in this direction for surface spreading methods. The lack of standardised predictive tools for clogging and adequate water quality monitoring has limited so far the development of more efficient management of MAR sites (Dillon et al., 2018). One main challenge is predicting clogging rates in advance and incorporating risks to derive cost-effective designs for MAR schemes (Maliva, 2020). Up to now, clogging rates have not yet been systematically related to parameters measured at the MAR scheme, to quantify clogging effects in a predictive way, accounting for site conditions and heterogeneities.

Hence, the necessity to extend the research to simulations of physical clogging processes from other engineering applications where water infiltration and drainage properties are vital for the system's functioning. These applications share similar features to MAR systems. In stormwater treatment, the physical clogging phenomenon can compromise the treatment performance of runoff water (Conley et al., 2020; Kandra et al., 2014; Wang et al., 2012). Similarly to vertical flow treatment wetlands, these sites consist of a filter bed with relatively low O&M costs; therefore, the clogging rate can determine the longevity of the system (Kandra et al., 2014). Cycles of saturation and desaturation regulate the infiltration of wastewater and water runoff, and the prevention of clogging is critical to maintaining hydraulic functioning and pollutant control (Nivala et al., 2012; Pucher & Langergraber, 2019). In geotechnical engineering, physical clogging issues are associated with particle erosion, transport and retention in granular filters due to seepage forces. Filters are applied to base soils, protecting earth-fill dams and preserving their stability from internal erosion. The filtering effectiveness is established by a stability and permeability criterion to prevent soil particles from passing through the filter voids and ensure constant drainage (Terzaghi et al., 1967). In petroleum engineering, infiltration occurs through water injections into the rock reservoir, forcing the oil towards the producing wells. The concomitant migration of particles inside the rock formation causes a reduction in permeability and, consequently, a decline in water injection and oil recovery (Roque et al., 1995). For injection wells, this process is identified by deep bed filtration (Bedrikovetsky et al., 2001; Wennberg & Sharma, 1997). The engineering fields dealing with water infiltration in natural heterogeneous systems are schematised in Figure 1.

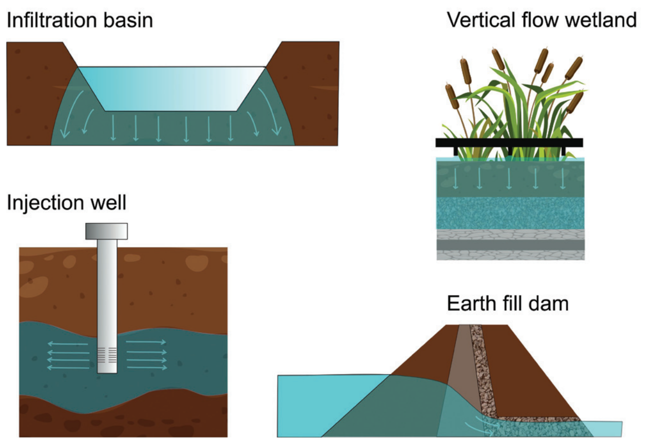

Fig. 1 - Examples of engineering applications in which physical clogging modelling has been studied in the literature.

Fig. 1 - Esempi di applicazioni ingegneristiche in cui la modellazione matematica del *clogging* fisico è stata oggetto di studio nella relativa letteratura.

The modelling approaches adopted in engineering applications could be transferred to MAR systems to fill the gaps in physical clogging predictions. Understanding deposition mechanisms and variations in hydraulic properties associated with physical clogging is needed to enhance MAR operations and anticipate potential system failure. This literature review organises the state of the art of physical clogging models to investigate their transferability for potential application to MAR sites. A systematic comparison is necessary to gain an overview of the models and relevant parameters controlling clogging. The predictive power of the models is discussed by examining to which extent they rely on parameters requiring calibration from a specific experimental configuration. The final scope is to provide concrete suggestions on formulas to describe clogging phenomena in MAR applications, especially for surface spreading methods, and derive a process-based workflow to be combined with site characterisation technologies. This work assists in developing a methodology to predict infiltration rates decline at specific MAR sites prior to construction. Incorporating the risk of physical clogging in MAR infrastructures' planning can enhance infiltration rates and limit the operation and maintenance (O&M) costs.

Materials and Method

The first step of the literature review was the collection of studies to evaluate the developed models for physical clogging processes critically. The literature review excluded experimental and observational studies limited to cause-and-effect relationships. The review was carried out by consulting the scientific database Scopus (https://www.scopus.com), Web of Science (https://www.webofscience.com) and integrating results from Google Scholar (https://scholar.google.com). The research covered academic papers, theses and conference proceedings.

First, the research focused on physical clogging models in MAR literature to understand the state of the art within the field. The research was then extended to other engineering applications, such as petroleum engineering, subsurface flow treatment wetlands, and geotechnical applications. The research's main keywords were always "physical clogging" and "modelling". The studies were collected and summarised within each application area, avoiding redundant studies. In addition, developed theories and relationships were highlighted by comparing and contrasting the work of later authors. The mathematical formulations representing the evolution of physical clogging were pointed out and organised in tables.

For classification and comparison, each study in the literature review was defined in terms of scope of application, model category, fines of interest and hydraulic operating conditions.

Results

Physical clogging investigations and modelling can differ significantly in engineering studies given the respective scope of application, study contextualisation and the goal to achieve through infiltration. Operating conditions control the dynamics of the physical clogging processes. In infiltration ponds, due to the applied constant head conditions, a decrease in soil permeability results in a decrease in flow rates. On the other hand, under constant flow conditions, such as in injection wells, clogging can lead to an excessive pressure head that can damage the aquifer formation (Reddi et al., 2005). Table 1 reports the modelling studies analysed in this review, and defines their field of application, operating conditions and fines of interest with the diameter range. The range of particles considered "undesirable" for each engineering field is site and objective-specific (Gibson et al., 2009). In stormwater or vertical-flow wetland applications, suspended solids (SS) are the fines of interest. For large particles (>30 μm) , volume phenomena dominate the interstitial and deposition process according to gravity and hydrodynamic forces (Herzig et al., 1970). Depending on the particles and medium grain size distributions, straining or size exclusion can occur, leading to the formation of an "external" or "internal" filter cake in the soil (McDowell-Boyer et al., 1986). The size of the fine particles of interest affects the deposition mechanisms taking place during infiltration. For deep filtration studies applied to injection wells, the fines of interest are colloidal and intermediate particles naturally occurring in the aquifer formation. Colloidal particles have a diameter size <1 μm, and surface phenomena control the transport and particles deposition given the physical-chemical properties of the suspension (Herzig et al., 1970). Brownian motion, electrostatic interaction and London-van-der-Waals forces regulate the attachment mechanisms (McDowell-Boyer, Hunt et al., 1986, Zamani and Maini, 2009). In contrast to larger suspended particles, colloidal particles have a slower sedimentation rate (Elimelech et al., 1998), and can accumulate in the pore throat, forming particles' bridges, which can be broken at high flow rates (Kanti Sen & Khilar, 2006). A comparison of the particles size diameters range for the fines of interest in the reviewed engineering field, is reported in Figure 2.

The operating conditions and range of fines of interest determine the choice of the numerical model to represent the physical clogging processes. The reviewed studies highlighted the following approaches to model the transport and deposition processes: (i) Macroscopic models, (ii) Probabilistic models, (iii) Analytical models and (iv) Conceptual models. The main equations and conceptualisation on the elementary volume of soil are underlined in each modelling approach. Tables 2, 3 and 4 show a transversal comparison of the mathematical expressions used by the reviewed authors in replicating individual clogging processes, namely the particles' transport and deposition (Table 2), porosity changes (Table 3) and following hydraulic conductivity (Table 4).

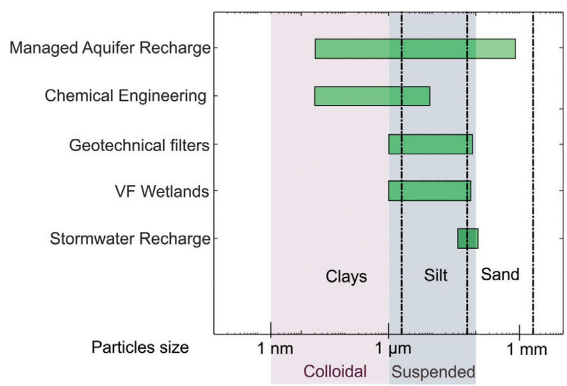

Fig. 2 - Particles size range (μm) for the fines of interest from the selected studies based on their field of application.

Fig. 2 - Intervalli delle dimensioni (μm) del materiale fine dagli studi selezionati sulla base del loro campo di applicazione.

Tab. 1 - Studies of physical clogging modelling, their relative field of application, model category, characteristics of the intrusive fines in experiments and the operating hydraulic conditions. NS= not specified.

Tab. 1 - Studi riguardanti la modellazione matematica del *clogging* fisico, campo di applicazione, categoria del modello, caratteristiche del materiale fine sospeso utilizzato e relative condizioni idrauliche dell'esperimento. NS= non specificato.

Reference	Applied field	Model category	Fines of interest	Hydraulic conditions
Pérez Paricio (2001)	Managed Aquifer Recharge	Macrosc. Model	Iron flocs (15-40 µm) Langerak case	Constant flow
Torkzaban et al. (2015)	Managed Aquifer Recharge	Macrosc. Model	Colloids (range NS)	Constant flow
Xie et al. (2020)	Managed Aquifer Recharge	Macrosc. Model	Suspended particles (2-800 µm)	Constant flow
Alem et al. (2013), Alem et al. (2014)	Filtration study	Macrosc. Model	Kaolinite (1.7 to 40µm)	Constant flow, Constant head
Wang et al. (2012)	Stormwater recharge	Conceptual	Suspended solids (38.5 – 75 µm)	Constant head
Blazejewski & Murat-Blazejewska (1997)	Vertical flow wetlands	Conceptual	Suspended solids (range NS)	Daily sewage flow
Hua et al. (2010)	Vertical flow wetlands	Conceptual	Suspended solids (range NS)	Daily sewage flow
Rege & Fogler (1988)	Chemical Engineering	Probabilistic	Kaolinite (0.02 - 0.2 µm) and emulsion droplets (2.2 – 9 µm)	Constant flow
Reddi et al. (2005)	Geotechnical engineering	Probabilistic	Kaolinite particles (1.0–12.0 µm); polymer microspheres were 1.0– 35.0 µm.	Constant flow, Constant head
Indraratna & Vafai (1997)	Geotechnical engineering	Analytical	Silica (20 - 80 µm)	Constant head
Locke et al. (2001)	Geotechnical engineering	Probabilistic and Analytical	base-soil particles (range NS)	Constant head

Macroscopic models

In macroscopic modelling, the clogging of a porous medium is described mathematically by the mass conservation and kinetic equations, describing the rate of clogging and the rate of decolmatage (Herzig et al., 1970). The porous media is considered a closed system (Fig. 3a), and starting from the mass balance under the assumption of unidirectional flow, the governing equations of granular filtration are approximated in the equation reported in Table 2(a). Iwasaki (1937) described the particle concentration profile through a filter in the form of an exponential decay function:

$$\frac{\partial C}{\partial z} = -\lambda C \qquad 1$$

With λ the filter coefficient. The filter coefficient evolves from the initial value λ_0, of the clean filter bed, at the initial stage, due to the accumulation of particles and alteration in the filtration action. This is expressed with the correcting factor $F(\sigma, \alpha)$, being α a vector of unknown parameters. The filtration performance and duration are further examined through the pressure drop measurements across the porous material. The evolution in the local pressure gradient is described through the factor $G(\beta, \sigma)$, relating the changes in permeability to the amount of deposited particles (Ives & Pienvichitr, 1965; Pendse et al., 1978; Zamani & Maini, 2009). Different expressions both for $F(\sigma, \alpha)$ and $G(\beta, \sigma)$ were derived fitting the observed effluent concentration profile and pressure drop changes through optimisation techniques. For a broad list of expressions from previous studies, see Bai & Tien (2000), Zamani & Maini (2009). Macroscopic models have mainly been applied in deep bed filtration to interpret the removal of colloidal particles from liquid suspensions. The physical clogging module of the model CLOG developed by Pérez Paricio (2001) for MAR applications is based on theoretical formulations and empirical dependences of filtration theory (Pérez Paricio, 2001). A mass balance equation involving coefficients for the attachment and detachment processes has also been adopted by Xie et al. (2020) to assess the risk of physical clogging by low-density floc particles from reclaimed water in MAR, shown in Table 2(c). In the work of Torkzaban et al., (2015), for sustainable MAR operations, the effect of changes in Ionic Strength (IS) and flow velocity has been investigated in soil cores with initial clay content, with the standard advection–dispersion equation with first-order kinetic terms for colloid release and retention, shown in Table 2(b). Advection-dispersion equations in clogging appear to be a favourable method for suspended colloids or clays when studying the significance of the ionic strength (Ye et al., 2019).

A limitation to using mass balances with kinetic equations is the requirement for parameterisation for particle deposition and remobilisation rates, which cannot be determined unless observed from experimental breakthrough curves (BTCs) in soil column experiments. The macroscopic models describe the filtration process as "overall behaviour" without

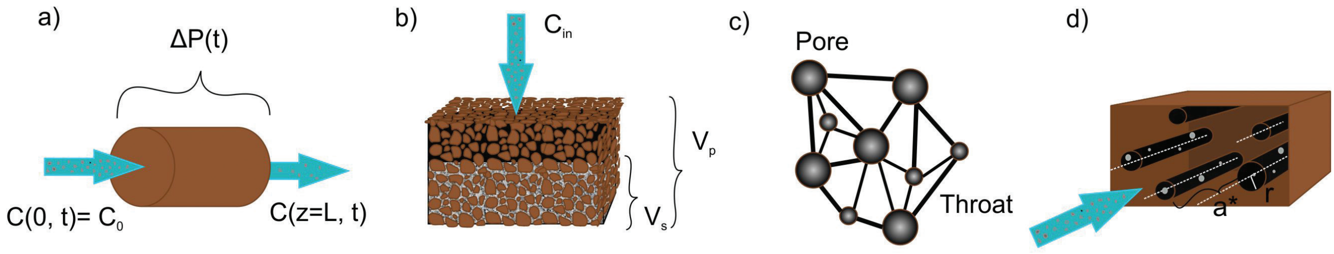

Fig. 3 - Different representations of the soil volume: a) soil elementary volume from macroscopic models, b) soil pore volume and volume filled with suspended solids from conceptual models, c) pore network models from probabilistic models, d) soil elementary volume as an ensemble of capillary tubes from analytical models.

Fig. 3 - Diverse rappresentazioni del volume del terreno: a) volume elementare secondo i modelli macroscopici, b) volume dei pori del terreno e volume riempito dai solidi sospesi secondo i modelli concettuali, c) modello basato sulla struttura porosa del terreno secondo i modelli probabilistici, d) volume elementare rappresentato da un insieme di tubi capillari secondo i modelli analitici.

describing its nature or mechanism (Zamani & Maini, 2009). Since parameter values change with varying particle size distributions and pore sizes, these models are not predictive in nature (Rege & Fogler, 1988). Moreover, observations of the filtration process are required and Wennberg et al. (1995) report that further parameter adjustment is needed for more complex situations during water injection in aquifers.

Probabilistic models

Probabilistic models in the literature represent particle transport and deposition as a combination of pore space events. A network model is generally adopted, based on a regular topology consisting of interconnected bonds intersecting at the nodes (Fatt, 1956). An example is shown in Figure 3c. The constriction sizes of the network are derived from the packing density conditions and the particle size distribution of the porous media. Combining the probability of the presence of the suspended particle with the probability of encountering a pore space, which reflects the conditions under which the particle will deposit or pass, the filtration process can be simulated with a probability function. In the work of Silveira (1965) and Witt (1993) a conceptual model of the pore network is used to determine the expected length of infiltration of suspended particles.

In Rege & Fogler (1988) the probability of particle capture is equivalent to the fraction of total flow in the annulus between the pore radius r_i and r_i-θa_j:

$$p(r_i, a_j) = 4\left[\left(\frac{\theta a_j}{r_i}\right)^2 - \left(\frac{\theta a_j}{r_i}\right)^3\right] + \left(\frac{\theta a_j}{r_i}\right)^4 \qquad 2$$

With θ a parameter indicating conditions favourable for deposition, r_i the radius of the pore tube i, a_j the radius of the particle j.

The likelihood of particles deposition by a direct interception on the walls of the pore tubes i is thus assumed under geometric and favourable conditions.

$$\theta = \theta_0 \exp\left[-\frac{\nu}{\nu_{cr}}\right] \qquad 3$$

With θ_0 lumped parameter depending on ionic strength and pH, ν the pore fluid velocity and ν_{cr} the critical velocity. Through the θ term, the model accounts for the hydrodynamic effect on the capture probability, given the critical velocity beyond which particles do not deposit. Reddi et al. (2000) adopted the same approach throughout the design of geotechnical filters, Table 2(e), using the basic principles of flow in cylindrical tubes and assuming that the elementary volume of the soil is an ensemble of capillary tubes (Fig. 3d). This simplification has been chosen by the author rather than the more rigorous network model and particle tracking approach reported by Rege & Fogler (1988). The effect of strain mechanisms is then accounted for by a pressure drop within the bond, and a new effective radius is calculated after N particles have been deposited, as shown in Table 3(c).

Probabilistic models present the advantage of accounting for the pressure drop evolution in the porous media using initially measurable parameters, such as the particle size distribution of the suspension, the sample's initial permeability, and the pore size distribution. In Rege & Fogler (1988) mercury porosimetry or photomicrographic techniques are suggested to determine the pore size distribution; in Reddi et al. (2000) the Haines method adopting increasing suction pressures is mentioned. Recent studies suggest 3D imaging techniques with X-ray micro-tomography (micro-CT) (Elrahmani et al., 2023; Xiong et al., 2016). However, in the illustrated approach, a limitation is represented by the likelihood of particles deposition, which depends on the ionic condition constant θ_0, and the critical velocity for particles wash-out ν_{cr}. These parameters cannot be readily determined and their calibration would depend upon experimental data from column trials. Reddi et al. (2000) suggest adopting values from similar studies in literature, such as the θ_0 reported in Rege & Fogler (1988) for bentonite suspensions, as well as the interstitial velocities in granular soils from the experimental work of Gruesbeck & Collins (1982), at which particle deposition is unlikely. Recent computational studies on pore-network models investigate the parameters affecting the likelihood of particle's deposition (Li et al., 2021; Lin et al., 2021).

Analitycal model

In the analytical model of Indraratna & Vafai (1997), the movement of noncohesive base-soil particles into granular filters is controlled by hydrodynamic effects. The soil element is represented as an ensemble of capillary tubes, defined by pores channels with a characteristic average diameter d_0, derived from the soil porosity and a mass-weighted equivalent diameter D_h (Kovács, 1981). The first geometric criteria assess the fraction of particles moving under gravitational transport for $d_i<d_0$. For particles with equal diameter size to the pore channels, an equilibrium between the external forces acting on the particle d_i is computed to determine whether the particles are transported under seepage forces. The critical hydraulic gradient acting on the particle at limit equilibrium, beyond which the hydrodynamic force overcome the frictional resistance, is:

$$i_z = \frac{4K}{\delta z y_w}\left(y_s h_s - y_w h_w\right)\tan\varphi' - \frac{2d}{3\delta z y_w}\left(y_s - y_w\right) \qquad 4$$

With $K = \tan^2\left[\left(\frac{\pi}{4}\right) - \frac{\varphi'}{2}\right]$ being φ' the effective friction angle of the material, δz is the length of the soil element, γ_s and γ_w respectively the specific weight of soil and water, h_s and h_w the height of the overlying soil and the hydraulic head.

The totality of loose particles passing through the pore channels, together with the pore water, is defined as slurry. The rate of particle transport is quantified through differential equations of conservation of mass and momentum, describing the evolution of the slurry density ρ_m and velocity u along the grid of soil elements. The formulations are reported in Table 2(d). A further extension of this analytical model of filtration has been carried out by Locke et al. (2001), who incorporates a deterministic equation for particle infiltration, based on a probabilistic approach derived by the filter void model of a 3D cubic network (Schuler, 1996). A similar approach for particle migration under hydromechanical effects has been followed by Federico (2017), who additionally implemented a model to derive the constriction size distribution and assess the migration length for the movable particles.

Due to their mechanistic nature, the analytical models have been developed without relying on empirical parameters from column experiments, only based on a priori information. Concerns for MAR application remain on the applicable boundary conditions for the model.

Conceptual models

A simple conceptualisation of physical clogging processes has been undertaken by Blazejewski & Murat-Blazejewska (1997) to address clogging in vertical-flow wetlands. The model considers the soil medium's initial pore volume and the time to fill up pores with the volumes of suspended solids (SS) daily delivered. An illustration of the filling of soil pore volume is provided in Figure 3.b. The time for clogging is computed in the following way:

$$t_c = \frac{\mathrm{v}_p}{\mathrm{v}_s} = \frac{\varepsilon_{ef} h_c A}{C_s^{in}\, Q/\rho_s\left(1-w_c\right)} \qquad 5$$

With C_s^{in} the mass concentration of SS in the inflowing sewage, Q the daily sewage flow, ρ_s and w_c the density and water content of SS, ε the porosity, A the area of infiltration and h_c the depth of clogging. The filled-up soil volume, and so the depth at which SS accumulate, is derived from the empirical equation from Burchak (1987), relating the effective diameter D_{10} to the depth of the heavily clogged sand layer:

$$h_c=150d_{10} \qquad 6$$

The relationship is valid for sands with $5x10^{-5}<d_{10}<3x10^{-6}$ m.

The reduction in soil permeability, based on the evolution of soil porosity, follows the solution of the Kozeny–Carman equation for uniform sphere particles from Bear (1988), Table 3(a).

Langergraber et al. (2003) found that the calculated theoretical clogging time is most sensitive to the density of the organic solids. The author related the clogging time to the load of suspended solids and the density of the organic solids $\rho_{TS,org}$:

$$t_c = \frac{\alpha \rho_{TS.org}}{C_s^{in} Q} \qquad 7$$

through the empirical coefficient α likely dependent upon the size distribution of particles and the bed properties (Kadlec & Wallace, 2009). However, Langergraber et al. (2003) reported a strong non-linearity between the remaining pore volume and the drop in the hydraulic conductivity in his pilot-scale constructed wetlands. This model assumes that all the larger pores are filled completely, which leads to a longer clogging time than the observed one.

The conceptual model from Hua et al. (2010) is also based on the available void space theory, developed by Blazejewski & Murat-Blazejewska (1997), additionally, it considers the fraction of washed-off SS in relation to a threshold flow rate. However, data from experimental wetlands are necessary to estimate the quantitative depth of clogging in relationship to the effective diameter D_{10}, and the evolution of the infiltration rate during the operation time. Similarly, Wang et al. (2012) developed a mathematical iteration model for clogging in urban stormwater aquifer recharge. The model is based on the accumulation of suspended solids and the formation of the clogging layer. Experimental data are necessary to quantify the clogging layer's critical thickness and hydraulic conductivity.

Discussion

The organisation of the reviewed studies allowed us to identify the main simulated processes and compare the adopted mathematical formulations in physical clogging.

Tab. 2 - Particles transport and deposition in porous media.

Tab. 2 - Trasporto e deposizione delle particelle nel mezzo poroso.

	Paper	Equation	Parameters
(a)	Iwasaki (1937); Herzig (1970); Zamani and Maini (2009), Alem et al. (2012)	Mass balance: $u\frac{\partial C}{\partial z}+\frac{\partial \sigma}{\partial t}=0$ $\frac{\partial \sigma}{\partial t}=\lambda uC$	• C=volume fraction of particles in suspension • σ= deposited particles volume per unit of porous media volume • u= Darcy velocity • λ= filter coefficient • τ=t-zϕ/u • ϕ= porosity
(b)	Torkzaban et al, (2015)	Mass balance: $\frac{\partial C}{\partial t}=\frac{D\partial^2 C}{\partial x^2}-\mathrm{v}\frac{\partial C}{\partial x}-\frac{r_{rel}}{n}-\frac{r_{ret}}{n}$	• r_{rel}=release rate of colloid concentration from pore walls • r_{ret}=retention rate at pore constrictions, in dependence of the ionic strength.
(c)	Xie et al. (2020)	$-\frac{\partial}{\partial t}(nC+C_s)+\frac{\partial}{\partial x}(Cv_x)=0$ $\frac{\partial C_s}{\partial t}=\alpha C-\beta C_s$	• C_s=the deposited particle mass in unit pore space (kg/m^3) • α = the particle attachment coefficient (min−1) • β = the particle detachment coefficient (min−1).
(d)	Indraratna and Vafai (1997) Locke and Indraratna (2001) Federico (2017)	Mass balance: $\frac{\partial(\rho_m u)}{\partial z}=\frac{\partial \rho_m}{\partial t}$ Momentum conservation $\sum F=\rho_m V_m\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial z}\right)$	• ρ_m= ρ_w V_w+$\rho_s V_s$/$V_w V_s$ density of the slurry • V_w =volume of water in each soil element • V_s =the summation of the soil particles volumes with d<d_0 • ΣF = sum of forces acting on the slurry
(e)	Rege and Fogler (1988); Reddi et al. (2000)	Deposition rate: $\frac{dN(r,a)}{dt}=q(r)p(r,a)C(a)$ $p(r_i,a_j)=4\left[\left(\frac{\theta a_j}{r_i}\right)^2-\left(\frac{\theta a_j}{r_i}\right)^3\right]+\left(\frac{\theta a_j}{r_i}\right)^4$	• N(r_i,a_j) = number of particles with radius a_j deposited in the pore tube with radius r_i • C(a_j) =the concentration of particles, expressed as number per unit volume • p(r_i,a_j) = probability of particles capture • q(r)=($\pi\gamma$J/8μ)r_i^4 flow rate in the tube (Poiseuille law) • a_j= the radius of the particle j • r_i= the radius of the pore tube i

Tab. 3 - Changes in porosity ϕ.

Tab. 3 - Evoluzione nella porosita` ϕ.

	Paper	Equation	Parameters
(a)	Blazejewski and Murat- Blazejewski (1997)	$\phi(t)=\phi_0-\frac{q_s t}{h_c\rho_s(1-w_c)}$	• w_c= water content s.s. • qs = daily suspended solids infiltration loads [g/m^{2}d]
(b)	Zamani and Maini (2009), Alem et al. (2012)	$\phi(z,t)=\phi_0-\frac{\sigma(z,t)}{(1-\phi_d)}$ $\phi_d=1-\frac{\rho_d}{\rho_p}=1-[\frac{\rho_w}{\rho_p}+\left(1-\frac{\rho_w}{\rho_p}\right)\frac{1}{a}N^{1-b}$	• ρ_d= the average deposit density; • ρ_p= the soil particles density; • N=number of particles in a deposit site • a=1, b=1.3
(c)	Rege and Fogler (1988); Reddi et al. 2000	$\frac{1}{r_{i,new}^4}=\frac{1}{r_{i,0}^4}\left\{1+3\sum_{j=1}^{M}N(r_i,a_j)\frac{a_j}{\alpha^*}\left[1-(1-\frac{a_j}{r_i})^2\right]^2K(r_i,a_j)\right\}$	• a_j=the radius of the particle j • r_i= the radius of the pore tube i • N(r_i,a_j) = number of particles with radius a_j deposited in the pore tube with radius r_i

Tab. 4 - Changes in permeability k.

Tab. 4 - Evoluzione nella permeabilita` k.

(a)	Blazejewski and Murat-Blazejewski (1997); Federico F. (2017); Pedretti et al. (2011)	$k=\frac{1}{5}\frac{\phi^3}{(1-\phi)^2}\left(\frac{D_m}{\alpha}\right)^2$	• α = shape factor; α =6 in Bear (1972) α =10 in Blazejewski and Murat- Blazejewski (1997) • D_m can be referred to mean grain size, harmonic mean, or geometrical mean
(b)	Reddi et al. (2000)	$k=C_s\phi\left(\frac{\gamma}{\mu}\right)\left[\frac{1}{4\sum_i^1\frac{f(d_i)}{d_i}}\right]^2$	• C_s= shape factor (1/32) • $f(d_i)$= volumetric frequency of the pore group d_i
(c)	Locke and Indraratna (2001); Koenders and Williams (1992)	$k=\frac{1}{\eta}D_m^2\phi\chi\left(\frac{\phi}{(1-\phi)}\right)^2$	• χ=0.0035±0.0005
(d)	Sherard et al. (1984); Indraratna et al.(1996), Indraratna and Vafai (1997)	$k=0.35(D_{15})^2$ $k=1.02(D_5D_{10})^{0.93}$	• D_x particle size (mm) in filter for which x% by weight of particles are smaller.
(e)	Torkzaban et al. (2015); Khilar and Fogler (1998)	$\frac{K}{K_0}=\frac{1}{1+\beta\sigma}$	• β= formation damage coefficient • σ = concentration of fine particles at the pore constrictions
(f)	Pérez Paricio (2001); Xie et al. (2020)	$\frac{K}{K_0}=\frac{\phi^3}{\phi_0^3}\frac{(1-\phi)^2}{(1-\phi_0)^2}$	
(g)	Alem et al. (2012)	$\frac{K}{K_0}=\frac{\phi^3}{\phi_0^3}\frac{(1-\phi)^2}{(1-\phi_0)^2}\frac{S_0^2}{S^2}\left(\frac{T_0}{T}\right)^2$	• $S=\frac{1}{1-\phi}\left[(1-\phi_0)S_0+(1-\phi_d)\frac{\sigma}{\rho_p}S_p\right]$ specific surface S_0 and ϕ_0 specific surface and porosity from clean bed; S_p and ϕ_d specific surface and porosity from of the deposited particles (Boller and Kavanaugh, 1995) • $T=\phi^{-m}$ tortuosity, with formation factor (Archie, 1942) m=1.3 for a sandy medium.

One of the main challenges remains the transport and deposition of suspended particles and, thus, the distribution of deposited particles along the soil profile (Table 2). The use of macroscopic models for colloid transport is recommended in the case of injection wells with highly treated water. This type of clogging can occur even in recharge wells with a low total suspended solids (TSS) concentration of 2 mg/L (Mays & Martin, 2013; Pyne, 1995). Deep-bed filtration studies from petroleum engineering can be appropriate in replicating particles' transport within the aquifer formation under constant flow injections. In this case, attachment mechanisms for colloids are influenced by surface forces, which depend on the hydrogeochemistry of the aquifer. For this purpose, parameters for attachment and detachment rates in kinetic equations have been calibrated from the observations of the BTCs on soil column experiments, as reported in Table 2(a), 2(b), 2(c) (Alem et al., 2014; Pérez Paricio, 2001; Torkzaban et al., 2015; Xie et al., 2020). An overview of each simulation study's share of empirical and physical parameters is provided in Figure 4. Physical parameters are intended parameters whose value can be determined from direct measurements, e.g., site characterisation.

Conversely, conceptual models developed in sub-surface wetland applications rely on an overly-simplified assumption of the pore volume, and the defined relationship for the clogging depth might be valid only on a narrow range of sands and suspended fines. Furthermore, the development of this modelling approach has required integrating empirical data from column experiments and experimental wetlands to quantify the thickness of the clogging layer and permeability variations (Hua et al., 2010; Wang et al., 2012). Probabilistic models have the advantage that they can be adapted to constant head and constant flow conditions starting from parameters that can be measured from soil samples (Reddi et al., 2005), although the pore size distribution requires specific laboratory equipment, and the simulations are performed at the pore-scale. As shown in Figure 4, the analytical approach of Indraratna & Vafai (1997) and Locke et al. (2001) is the only model, accounting for SS transport and deposition processes, independent of empirical parameters.

In MAR surface spreading systems recharged with no pre-treated water, the incoming suspended solids mainly cause physical clogging, similar to vertical flow treatment wetlands and stormwater infiltration systems. This study revealed

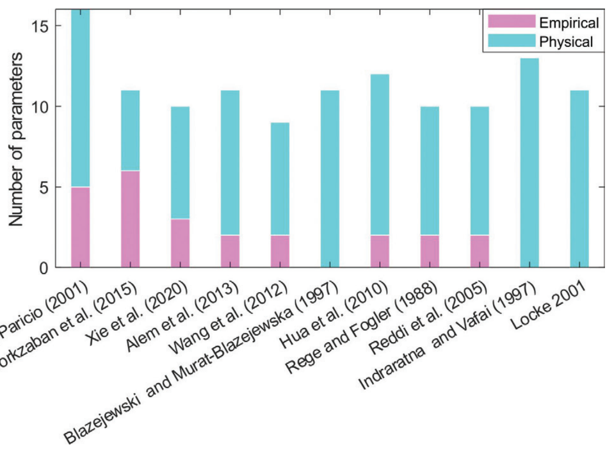

Fig. 4 - Number of parameters in each model for physical clogging from the reviewed studies.

Fig. 4 - Numero di parametri nei modelli di *clogging* fisico all'interno degli studi revisionati.

that numerical models based on geometric consideration for particle entrapment might be more suited to account for volume phenomena for suspended solids deposition. Surface spreading systems should incorporate a geometric and hydraulic component to model physical clogging processes in MAR surface spreading methods. A process-based framework is presented in Figure 5. The geometric component defines the geometric parameters for particles entrapment, as done in previous studies, based on the ratio of the diameter size of fines $d_{p,x}$ to the size of the pore constrictions $d_{0,x}$, or porous media diameter size $d_{g,x}$ (Gruesbeck & Collins, 1982; Herzig et al., 1970; Muecke, 1979). The variation in the soil porosity can be computed from the volumes of deposited particles inside the porous media, as schematised in Figure 5, similarly to most of the examined numerical models (Table 3). The morphology of the formed deposits can be included in the computation of the new porosity, considering the deposits' average density (Alem et al., 2013; Boller & Kavanaugh, 1995). This literature review also highlighted that most authors agree with using the Kozeny-Carman equation (Carman, 1937; Kozeny, 1927) in computing permeability reductions due to deposited particles (Table 4). The Kozeny-Carman model assumes the packed bed as an ensemble of capillary tubes through which the fluid flows in laminar conditions according to Poiseuille's law, under saturated conditions. The permeability k is in function of the two main packing material properties: the specific surface area and the packing density. As shown in Table 4, some authors prefer to use the normalised form of the Kozeny-Carman model (Alem et al., 2013; Pérez Paricio, 2001; Xie et al., 2020), while others update the soil permeability directly from the variation in soil structure (Blazejewski & Murat-Blazejewska, 1997; Indraratna & Vafai, 1997; Locke et al., 2001; Reddi et al., 2000). The normalised form of the Kozeny-Carman equation can improve predictions in the reduction of hydraulic conductivity, starting from the initial measured value and consequent reduction in porosity space and increase in surface area. Moreover, a process-based model for physical clogging should also account for the evolution of the filtration action of the porous media. Time-dependent parameters could depict the evolution of the media filtrating capability based on the already deposited particles from the previous filtration history. The self-filtration process would affect the geometric component by modifying the grain size distribution and the hydraulic component with the evolution in the soil permeability, as illustrated in Figure 5. This effect can be replicated in process-based models for MAR application.

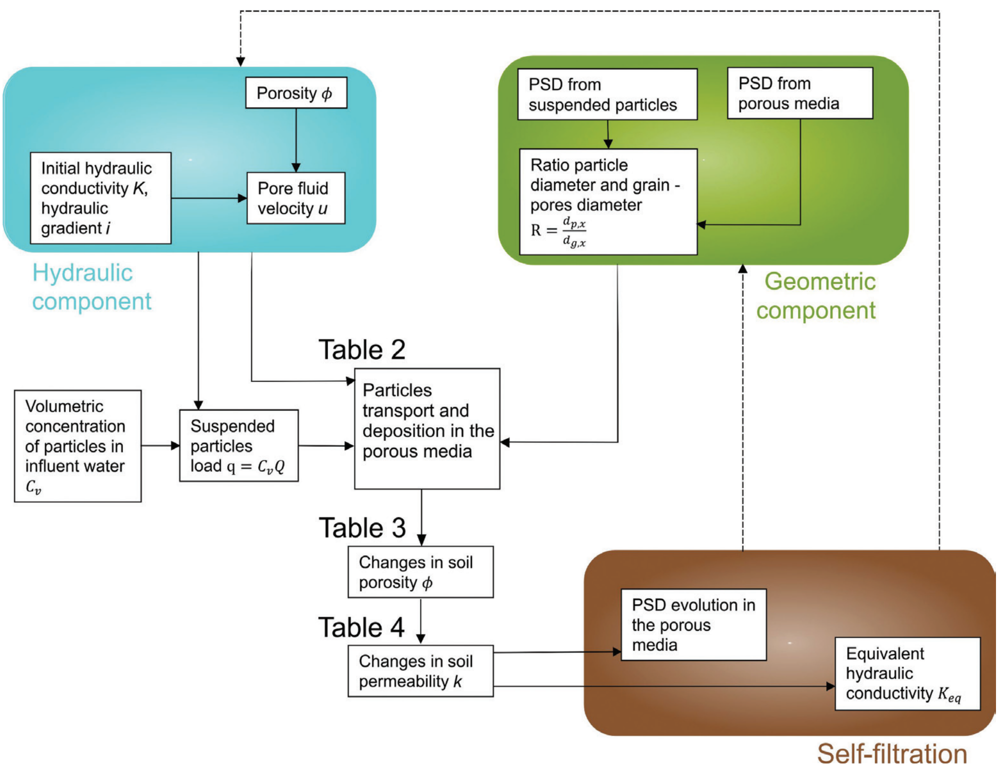

Fig. 5 - Process-based framework for physical clogging modelling in surface spreading methods.

Fig. 5 - Inquadramento dei processi fisici e schemi concettuali per la modellazione del *clogging* fisico per gli impianti di ricarica.

The advantage of the presented framework (Fig. 5) is that it can be further developed to be parameterised with data from site characterisation. The collection of recharge water data, particularly TSS and particle size distribution (PSD), can be used to predict the effect of straining on the sediment matrix, to derive the relative reduction in hydraulic conductivity and total infiltration capacity (Lippera et al., 2023b; Lippera et al., 2023a). This framework can be transferred to multiple MAR schemes and adapted on the base of the sediments' heterogeneities, characterised by initial hydraulic conductivity, porosity and grain size distributions. The depth of the resulting clogging profile from the simulation of deposition processes can assist MAR operators in the previsions of appropriate cleaning techniques based on the expected soil depth to be treated. This methodology can also determine the expected frequency of cleaning schedules when the total infiltration capacity reaches a low threshold. In planning the MAR site, the drying and cleaning periods should be included within the definition of hydraulic loading rates (Bouwer, 2002).

Conclusion

From the wide variety of models in the literature to predict physical clogging, it is not straightforward to derive the relevant relations for applied hydrogeological purposes, which is crucial for MAR feasibility studies. This literature review provides a modelling framework to assess the risk of physical clogging at MAR sites. It is intended to offer guidance on the use of existing models and to identify gaps that need to be closed to assess this risk with field parameters. The main physical clogging processes were identified and mathematical formulations were compared from the reviewed studies. The review showed that predicting particle transport and distribution is the main challenge in modelling physical clogging. The studies that attempt to model clogging on the overall volume of soil rely on the implementation of column experiments, for which the validity of such parameters remains constricted to the specific experimental set-up. Whereas attachment and release mechanisms are described with a probabilistic or analytical approach, these processes are computed at the pore scale and boundary conditions need to apply. To overcome this challenge, a process-based physical clogging model for surface spreading methods should possibly integrate hydraulic and geometric components to quantify fines retention in heterogeneous sediments at MAR sites. The review also proved the Kozeny-Carman model to be the most popular equation in replicating evolutions in permeability, given the variations in soil porosity from the deposition of particles. The Kozeny-Carman model can be adapted from physical parameters in soil samples' data. Thus, a compromise between a overly-sophisticated predictive model and an empirical one calibrated under a single-column experiment should be adapted to assess the risk of physical clogging for MAR sites from site characterisation data. The proposed methodology breaks down the complexity of clogging. However, in future it could be extended to include other clogging processes, e.g. biological and chemical, to provide estimates of the overall risk of clogging.

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Competing interest

All authors, the corresponding author states that there is no conflict of interest.

Author contributions

Studies collection and data processing, Maria Chiara Lippera; writing-original draft preparation, Maria Chiara Lippera; writing-review and editing, Thomas Vienken, Ulrike Werban; supervision, Thomas Vienken, Ulrike Werban; project administration, Thomas Vienken, Ulrike Werban. All authors have read and agreed to the final version of the manuscript.

Additional information

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