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Clogging mechanisms and preventive measures in artificial recharge systems

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Abstract: Groundwater which occurs in fractured rock or porous aquifers or other geological weak zones such as faults and fractures is usually extracted via boreholes, hand wells or other sources such as springs. Water scarcity has become a severe problem due to many factors, such as an alarming increase in population and per capita water consumption, over exploitation of groundwater resources and abrupt global climatic change along with its related eco-environmental geological problems. In such situation, application of artificial recharge systems (e.g. surface recharge basin and deep injection well systems) can help to effectively manage and augment the unitization of groundwater resources. However, the clogging problem, which may be caused by a complex interdependent mechanisms of physical, chemical and biological has been a challenge for the efficacy and the implementation of recharge facilities. Clogging can reduce the permeability, recharge rate and longevity of recharge facilities and increase the operational and maintenance costs. Major influencing factors associated with the occurrence of clogging include the chemical composition of groundwater (both the recharge water and native groundwater), aquifer medium and microbial diversity, together with other environmental factors such as temperature, pressure, total dissolved solids, total soluble salts, pH, Eh, nutrients, gases, carbonates and others; these factors ultimately increase the piezometric head but reduce the permeability and infiltration rates of porous/seepage media. Pretreatment of recharge water can minimize the potential clogging. In the case of clogged wells, rehabilitation methods need to be deployed. In the meantime, there is an urgent needs to understand the basic causes and developmental processes/mechanisms of clogging in order to mitigate this problem. This paper reviews the major clogging mechanisms and their possible preventive measures and redevelopments in artificial recharge systems.

Keywords: Artificial recharge; Clogging mechanisms; Groundwater; Prevention; Redevelopment

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Introduction

The penetrated and retained water occupying all the voids of associated geological strata under the earth's surface is termed as underground water, or otherwise, groundwater (GW). Approximately 97% of the world water in the oceans is salty water and two-thirds of remaining fresh water in confined (mountainous and arctic) regions is entrapped as ice. 98% of the liquid water is groundwater, whereas streams, rivers, and lakes hold only about 2% (Bouwer, 2002). Groundwater exists in soils and rocks. Generally, in the aeration zone or unsaturated zone, both water and air filled the gaps between the soils, while underlying this layer is the saturated zone where only water fills the void spaces, i.e. aquifer, and water in the aquifer is termed as groundwater. Groundwater as a renewable and important natural resource serves many purposes, such as (i) domestic water supply, for the public and private

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sectors (e.g. about 75% use in Europe); irrespective of intensive research on water reuse, desalination processes as well as advanced treatment techniques (Jørgensen and Stockmarr, 2009); (ii) agriculture use which mainly includes irrigation, animal watering and agricultural productions; and (iii) industrial and construction uses. In addition, groundwater has been increasingly used in the areas of energy such as aquifer thermal energy storage (ATES) projects (Van Beek, 2010). In artificial recharge-discharge systems, groundwater has recently been extracted for controlling temperatures of different engineering structures by using heat pumps due to its sufficient availability and unique property of relative constant temperature throughout the year. This eco-friendly technology allows the groundwater with heat energy to be abstracted and then injected into the aquifer through an injection well during the winter. Similarly, in summer, the water is usually pumped to reduce the temperature of different engineering structures. By pumping water into the wells, the groundwater recharge can be artificially carried out by applying the induced artificial recharge process. Although similar in design, the major difference between the artificial recharge and water supply wells is that the surrounding aquifer recharged with water flowing from the recharge well is driven by either injection pump induced head or a gravity head (California Water Plan Update, 2013). In an injection well system, a substantial amount of water is being pushed through a small aquifer volume.

In an artificial recharge system (ARS), however, clogging is the major problem for the recharge system to work smoothly and is often influenced by different interdependent physico-bio-chemical factors that may have different behaviors in porous and fractured media (Baveye et al. 1998; Constaninos et al. 2010). Clogging can also reduce the flow to the aquifer due to the blockage of some available pores, which ultimately reduces the permeability of the porous medium (Mays and Hunt, 2005). In many cases, injected water with low quality can cause the clogging in deep wells. These injected effluents usually undergo secondary biological processes such as the combination of extended aeration and/or aerobic digestion; among them, high concentration of suspended solids (SS), biochemical oxygen demand (BOD), N-compounds, and grease and oil often may remain in these effluents for quite a long time. In addition, during water injection some other factors such as SS, total dissolved solids (TDS), sodium adsorption ratio and certain nutrient concentrations are also of great concern. These factors might stimulate microbial activity and can cause clogging in the surroundings of injection well, the influence of which can span further into the aquifer system (Rinck-Pfeiffer et al. 2000). According to Dillon and Pavelic (1996), 80% of the aquifer storage and recovery sites faced clogging problems, approximately half of which were caused by physical clogging due to the SS infiltration, while 15% were caused by biological growth and microbial activity and 10% were attributed to chemical precipitation. There were also other clogging processes, i.e. 10%-air entrapment, 5%-clay swelling and dispersion, and 5%-mechanical jamming and mobilization of aquifer sediments. Therefore, by considering these cases, it is necessary to pay attention to conceptual issues of the well clogging problem in order to develop eco-friendly and economy-wise strategies for combating this nuisance global problem. The present paper attempts to review the basic mechanisms, types, and characteristics of the recharge well clogging together with the potential methods, measures & redevelopments for clogging prevention and remediation in artificial recharge systems.

1 Groundwater recharge

Replenishment of an aquifer with water is defined as a recharge process (RP). This is termed as natural process when precipitated water percolates or filtrates via soil pores or rock fractures into an aquifer. Natural recharge process of groundwater (GW) strongly depends on local climate and the properties of vadose zone and aquifer. Contrarily, in artificial recharge (AR) system, water is introduced on or into the ground where the applied surface water is infiltrated and moved down to aquifers to enhance GW pools or resources. Briefly, an AR process involves the transmission of water present at surface towards the subsurface aquifers via anthropogenic interventions. Bouwer (2002) reported that this water transmission is done by water accumulating the water on the surface of soils or rocks with special structures such as furrows, basins, ditches and others or by introducing it to the infiltrating trenches, shafts, or vadose zone wells, or directly injecting it into the aquifer via recharge wells. Generally, there are three ways of AR, i.e. (i) surface infiltration basin (mostly installed in soil layers preferentially with sandy soil and limited clay), (ii) recharge wells sunk in vadose zone where surface infiltration is difficult due to hydraulic properties and economic factor, and (iii) injection well with direct recharge to confined aquifers. In most cases, the AR is achieved by pumping and injecting water into the wells or by deploying water on upper layers, following by its seepage into the aquifer involved through the unsaturated or vadose zones. The augmentation of GW reservoirs by AR can be considered as a supplemental activity to the natural recharge process. It is hence a useful approach to enhancing the groundwater availability and improving water quality of the aquifer. However, the most critical issue that challenges the efficiency of different recharge systems is clogging. Therefore, understanding the types and mechanisms of clogging in artificial recharge systems and their possible control measures will provide the conceptual framework to mitigate the clogging problem.

2 Types and mechanisms of clogging in artificial recharge system

2.1 Processes and mechanisms of clogging

Both surface and deep recharge systems may encounter clogging problem. Van Beek (2010) reported that a well clogging can be characterized by the decrement of specific capacity, i.e. the discharging rate (m^3/h) divided by the drawdown (m) which is the water level difference between the operational well and resting state. He reported that the system clogging could be attributed to mechanical (well bore) and/or chemical (screen slot) causes in the wells which abstracted GW from unconsolidated aquifers. The characterization of screen slot clogging is done by increasing the difference in water levels during GW abstraction, while the well bore clogging is done by the absence of the increase of water level difference. Bouwer (1999) documented that the clogging problem can be caused by either (i) inorganic SS (silt and clay particles) or organic SS (sludge and algal bloom) in the water, and (ii) by the growth of microorganisms on the soil particles as microbial biofilms are followed by production of polysaccharides and other water insoluble products such as metabolites, resulting in the formation of a soil-clogging biomass matrix. Some microorganisms can also release the gases such as N_2, CH_4 and CO_2 that can clog soil pores and ultimately reduce the soil porosity. Gasification might also occur in the aquifers where entrained air is present in the water of recharge wells or the recharged water has lower temperature than that of the GW. During the warming process of the recharge water in an aquifer, dissolved air might escape from solution resulting in the formation of air pockets that can block the pores in the aquifer; this is the phenomenon termed as air binding. Furthermore, the artificial recharge process often leads to the occurrence of Fe and Mn (hydro)oxide precipitates in the well due to the change in dissolved O_2 levels; and the $CaCO_3$ precipitation is ascribed to the change in CO_2 content in the solution and the changes in pH (Bouwer, 2002).

In general, a recharge system clogging is likely to occur due to the operation of the system. Its intensity is largely dependent on quality of the recharging water. On the other hand, the aquifer and GW properties, and the construction borehole and the recharge facility have great impact on the clogging process (Fig. 1). In particular, the clogging problem preferentially occurs on the infiltrating surfaces such as the recharge basin bottom, trench wall and the wells in both vadose zone and aquifer system. As a result, it ultimately diminishes the infiltration rate, injection rate and aquifer permeability near the injection well. An enhanced flow resistivity close to the recharging point is a clogging index in ARS, which is in close relation to the quality of recharging water, physical attributes of seepage media such as mineral and grain compositions (Zheng et al. 2018).

2.2 Methods for potential clogging rate

Potential clogging rate for an artificial recharge system can be predicted by using different methods (Rinck-Pfeiffer et al. 2000) which include modified fouling index (MFI) (Hutchinson, 1997), parallel filter index (PFI), organic carbon (OC) content i.e. assimilable organic carbon (AOC) and biodegradable organic carbon (bDOC) contents of the recharging water, as well as mathematical, empirical and analytical models (Rinck-Pfeiffer et al. 2000; Masciopinto et al. 2017; Arfan et al. 2020; Yifru et al. 2020; Wei et al. 2020). The MFI describes SS contents of the water. The AOC is a microbial determination protocol that relies on plating and incubation technique of water sample for Pseudomonas fluorescence type bacterial growth followed by counting number of bacterial colonies. The results in protocol are expressed on the basis of acetate solution's carbon concentration yielding the similar microbial growth.

As the AOC is usually less than 1% of dissolved OC (DOC), the bDOC may be a better parameter for the estimation of biological clogging compared to the AOC, especially when the OC concentration is high. In addition, it is more feasible to determine the bDOC content than that of the AOC, because

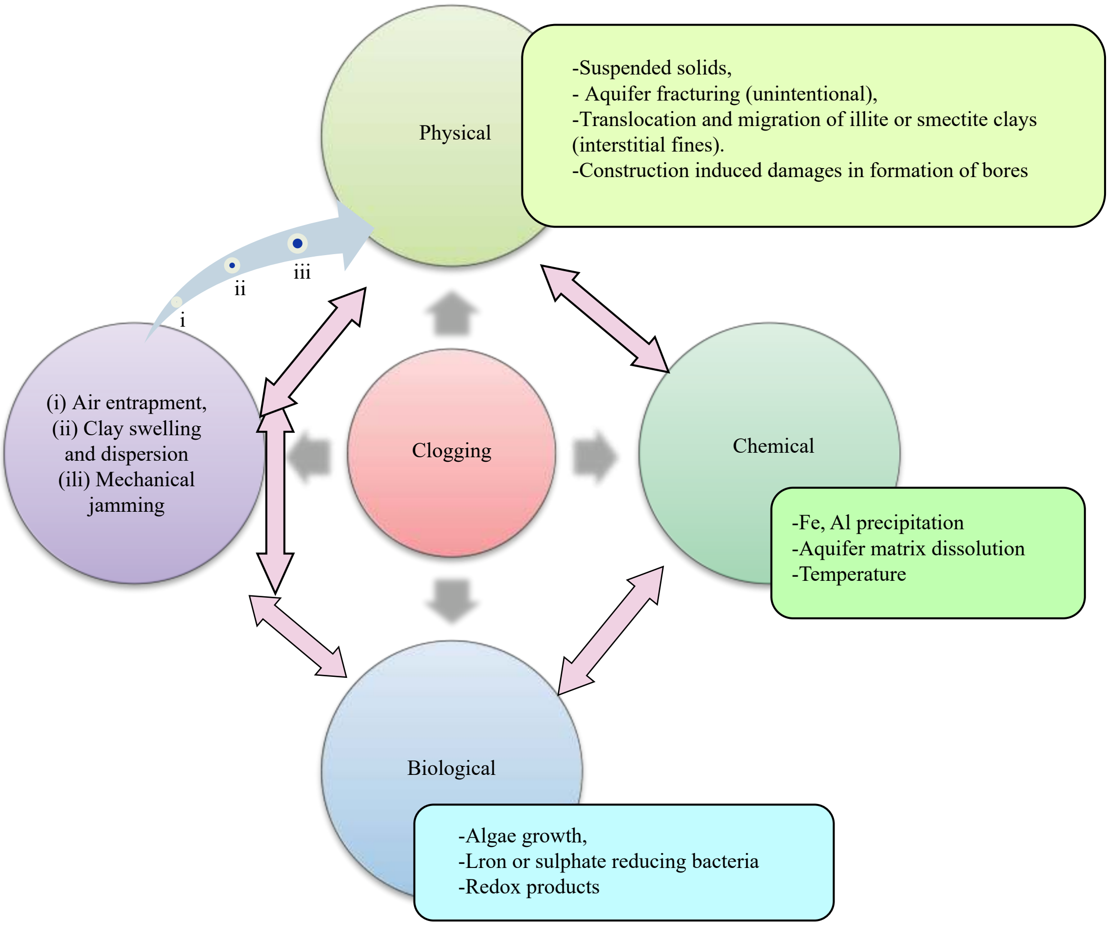

Fig. 1 Conceptual framework of the types of clogging that can occur during the recharge process

the bDOC test relies on the degradability of OC in different soil tests i.e. columns or soil slurry batch tests. The estimation of PFI relies on the flow of recharging water through appropriately packed columns with suitable aquifer materials. Thus, an advanced alarming factor can be established due to the faster clogging rate in columns compared to field tests (Bouwer, 2002). The MFI indicates the inversely filtered flow slope versus filtered volume on a cumulative basis, which is the best parameter to predict clogging potential of the water that penetrates into the aquifer. Comparatively, the other clogging parameters such as SS content, bDOC and flow tested in packed columns might have some limitations as the indicators of relative clogging potentials. However, these parameters might not be suitable for actual clogging prediction because the injection rate might decline in a recharge operation (Bouwer, 1996). Therefore, more detailed study on full scale recharge well test is direly needed to formulate the criteria for a better design and management of recharge well. Furthermore, a timely recognition of clogging generally provides valuable information to restore the original capacity of the system by deploying an appropriate redevelopment approach. However, the predictability of well clogging remains questionable, in spite of many efforts have been made by using different parametric indices for both physical (e.g. total SS and turbidity) and biological (e.g. total OC, DOC and AOC) cloggings. There is a general reduction in concentrations of BOD, SS, pathogens, and N along with the water infiltrates through vadose zone (Johnson et al. 1999). Sallès et al. (1993) reported that there is generally no analytical or numerical/mathematical tool to study the deposition and clogging of the porous media. Using modeling approach to predicting well clogging problem has been a challenge due to the interdependence and diverse natures of soil clogging mechanisms. Mathematical models used for predicting the movement of suspended particles (SP) in the aquifer are unable to verify the experimental data due to the variability of associated parameters and soil and environmental conditions.

2.3 Types and mechanisms of clogging

Different types, causes, and mechanisms of clogging based on the cases reported in the pertinent literature (Baveye et al. 1998; Bouwer, 2002) are summarized in Table 1. It is hard to distinguish the clogging mechanisms due to the interdependence of cases studied and complexity of well clogging. For example, reactive models can simulate different scenarios of temperature perturbation, which is in relation to potential clogging risk, i.e. the precipitation of carbonate, calcium sulfate and clay minerals taking place in the "hot bubble" and the precipitation of barium sulfate and clay minerals in the "cold bubble". Well clogging caused by SS can be recognized as a practical implication of microbe mediated reactions in soil. Similarly, it is hard to distinguish the processes of bioclogging and chemical clogging because some reactions in chemical clogging are mostly the microbial mediated ones. Hence, the uncoupling of clogging process is a challenge in practical situations.

Generally, clogging can be categorized as (i) mechanical/physical clogging due to suspended particulate matter in the water, (ii) chemical clogging due to chemical reaction and substance precipitation in the aquifer, and (iii) biological clogging due to the accumulation of microbial/algal slimes and resultant redox products. Intrinsically, clogging is a physical phenomenon. In the meantime, it is also an interdependent and complex result of various physical, biological, and chemical processes, each of which is the combination of numerous processes impacted by different factors. For example, physical clogging may arise due to the presence of SS in recharging water, clay swelling and dispersion and mechanical jamming, etc.; the latter two that affect different types of clogging are separately categorized in few studies. Similarly, bioclogging may be due to microbial cells, extracellular polymers, gaseous byproducts, or microbe mediated insoluble precipitates (Baveye et al. 1998; Camprovin et al. 2017). The chemical clogging phenomenon is extremely intricate because of different influencing factors that are acting as developmental agents in the chemical clogging. These influencing factors include the chemical components of the recharging water and groundwater in the aquifer, mineral composition of the aquifer media and environ-

Table 1 Major clogging types and various influencing factors/causes and processes

Clogging types	Factors/causes	Processes
Physical	(i) The presence of suspended matter such as inorganic (clay, silt, etc.) and organic (organic matter, algae, sludge, etc.) in recharge water (ii) Presence of colloidal material and dispersal of clay particles due to ion exchange between recharging water and aquifers (iii) Mechanical compaction of aquifer materials due to high injection processes	(i) Filtration and deposition of suspended solids (SS) by the porous media, i.e. Filter function (diameter of SS > diameter of media pores) and deposition function (SS deposition on the pore wall due to gravity) *(ii) Swelling of clays and dispersion *(iii) Mechanical jamming and mobilization of aquifer sediments
Chemical	(i) Recharge water (aerobic), and native groundwater (anaerobic) containing soluble iron and manganese and aquifer material producing insoluble precipitates of iron and manganese oxides or hydroxides, e.g. formation of iron flakes from native ground water due to recharge of water with a pH and Eh in the range of ferric iron (ii) Mineral gradients of aquifers (iii) Environmental factors such as temperature and pressure, etc. (iv) Entrained air in recharge water	(i) Blending and geochemical reactions between the recharge water and native groundwater resulting in the formation and chemical precipitations of insoluble precipitates of Fe and Mn (hydr)oxides (ii) Mixing of cooler recharge water with native groundwater and the removal of dissolved air from the solution, i.e. the presence of air bubbles in the recharge water entering a well resulting in air entrapment or entrainment *(iii) Release of dissolved gases resulting in pore blocking air pockets in the aquifer, termed as air binding (iv) Dissolution/precipitations of $CaCO_3$ due to changes in pH and CO_2
Biological	(i) The growth of bacteria (e.g. iron and manganese) and algae in the gravel pack and the surrounding formation (ii) The concentration of dissolved organic carbon (DOC), organic material, total nitrate, total phosphorus, and temperature etc. (iii) Microbial mediated gas productions (nitrogen, methane, CO_2)	(i) Development of microbial growth and accumulation of cell bodies in the porous medium resulting in biofilms (ii) The production of bacterial extracellular polymers or polysaccharides forming soil-clogging biomass (iii) Microbial mediated accumulation of insoluble precipitates and redox products (iv) The entrapment of gaseous products resulting in soil pore blocking

*Clogging due to clay swelling and dispersion, mechanical jamming and air entrapment can be categorized into separate clogging categories.

mental factors such as temperature, pressure, etc. In chemical clogging, chemical precipitation, and behavior of certain metal ions such as iron (Fe) and manganese (Mn) are extremely important.

3 Physical clogging

3.1 Clogging by suspended particles

Physical clogging occurs when small particles are deposited and detached during transport process (Ahfir et al. 2009). Suspended particles (SP) in the recharging water, soil size and porosity are the key factors for particle deposition. Physical clogging involves transport process, attaching process (deposition and retention) and de-attaching process (shearing and unclogging) of inert SP in the recharging water, resulting in the diminution of porosity of infiltrating space (Pérez-Paricio, 2001). At the same time, it gradually reduces the aquifer permeability and consequently the infiltration rate of recharge system, which has restricted the application of AR techniques in many areas. It was reported that approximately 70% of reduction in permeability of a recharge system was attributed to physical clogging (Reddi et al. 2000).

Physical clogging can be classified into two types. The first type is the presence of SP in the injected water and the second one is the mobilization of finer soil particles in the aquifer triggered by the injection process (Fig. 2a-Fig. 2b). In terms of their particle composition, the SPs can be categorized into: (i) colloidal sized particles with particle size of less than 1 μm; (ii) intermediate particles (size: 1-30 μm); and (iii) large sized particles (>30 μm). In an AR system, physical clogging may change over time due to the change in controlling forces such as those changed from volumetric to surface forces and vice-versa; and this behavior relies on flow velocity as well as the availability of reactive surfaces (Zamani and Maini, 2009; Pedretti et al. 2011). Brownian diffusion also displays some significant function in characterizing the fate of colloidal fraction in the porous media. The formation of colloids can take place with the substance sourced from inorganic constituents, humus, and biological products (Pérez-Paricio, 2001). The GW usually has a low concentration of colloid; but this content can be changed due to chemical reactions in the water which induce the occurrence of colloid because of repulsive interactive forces occurring between colloidal fraction and grain formation (Ryan and Gschwend, 1994). The variations in soil reaction (pH) and strength of ionic species are important factors in this context. Repulsive forces between particles can enhance and induce remobilization of colloidal fraction, when the injected water has less strength of ionic species than that of groundwater (Mc Neal and Coleman, 1966). Swelling and dispersion mechanisms of clay are related to this phenomenon. The pH augment enhances the dispersion of clay which ultimately leads to the reduction of the medium permeability (Pérez-Paricio, 2001). The unfavorable impact due to the quality of recharging water and aquifer media highlights the concern about clay swelling and dispersion. These fine-grained clay particles with negatively electronic charges are present in the form of threads, plates/flocks and they are normally bonded with the other positively charged particles. Although, some authors classified mechanical jamming (i.e. particle rearrangement) and clay expansion or dispersion into separate clogging categories, these clogging methods might be considered as specific categories of clogging caused by physical process as listed in Table 1. Filter function (where the SP particle size is larger than that of media pore space) and deposition function (in which the SP deposes on pore wall due to gravity) are the major reasons for physical clogging due to the SP. Different experimental results have shown that recharge water for aquifer storage and recovery (ASR) should have a safe limit of SS <2 ppm (Rinck-Pfeiffer et al. 2000). Nevertheless, it is also reported that some aquifers with a high level of SS did not cause clogging because GW in the aquifer contains $CaCO_3$.

In a surface-based system clogging, a proportional relationship exists between the clogging potential degree vs. surface clogging layer thickness and the SP concentration of recharged water. Generally, the focus for investigating physical clogging has mostly been placed on the surface of seepage zone (Kristin et al. 2005), with limited ones on the inner part of the seeping zone. This is dependent on the seepage media properties, recharging water quality, particle size and its physicochemical characteristics, seepage capacity and recharge time duration (Huang, 1993). However, translocation of finer-grained materials, particularly clay colloids, is a recurring challenge for recharge systems to operate efficiently. Released clay colloids interact with surfaces (Torkzaban et al. 2015), which will ultimately block the entire vadose and greatly reduce its permeability. Due to the infiltration and movement of water in vadose zone, separation of foreign and inert material takes place via different processes. The large particles

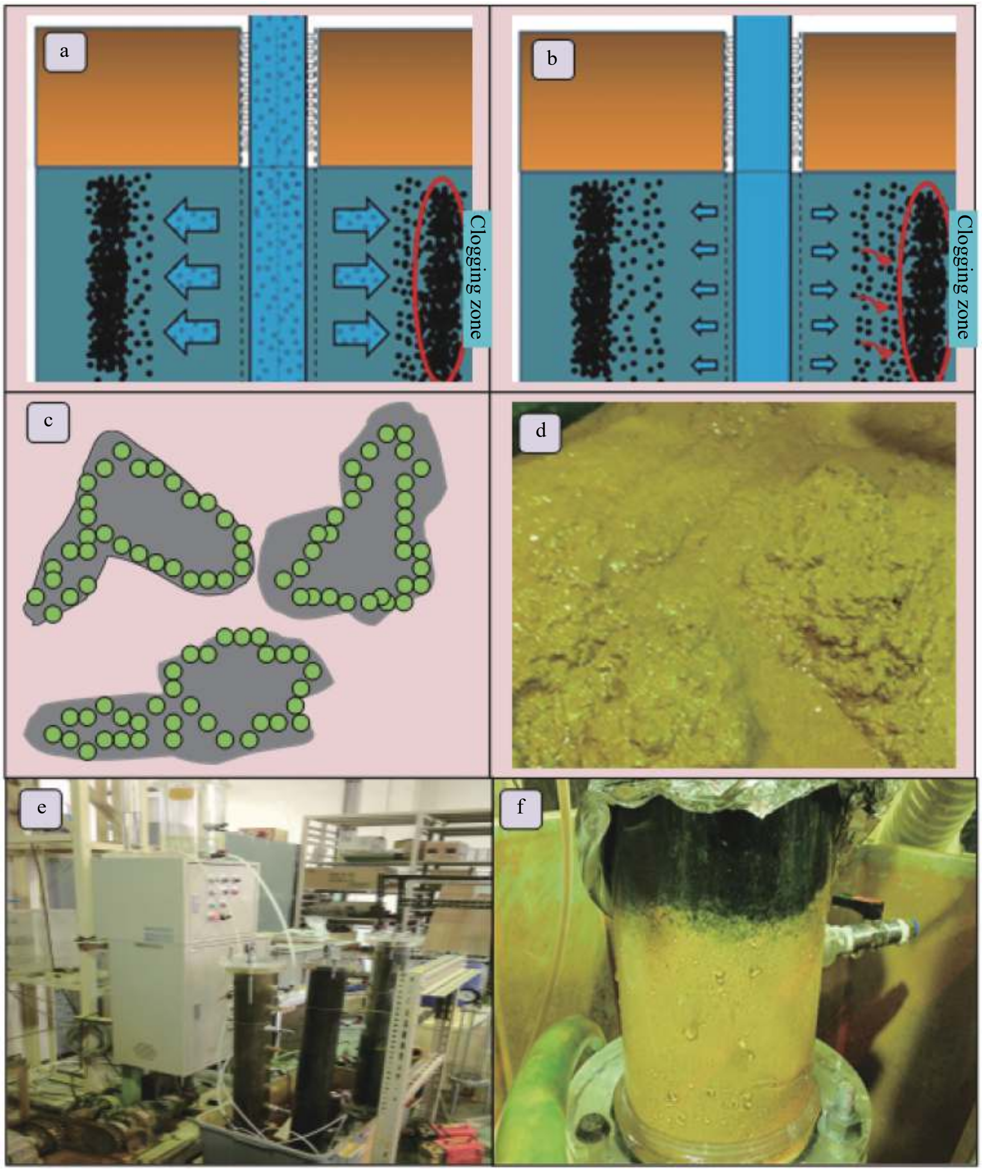

Fig. 2 (a) Physical clogging due to the suspended particles initially presented in the injected water; (b) Physical clogging due to the presence of fine soil particles from the aquifer; (c) Lay out of microbial biofilm that can cause bio-clogging; (d-f) Deposited insoluble iron flakes produced upon the oxidation of soluble iron (Fe^{2+}) in a column experiment resulting in chemical clogging

with the size ranging from 1 µm to 10 µm either deposit as a surficial layer or are filtered by the topsoil, while the smaller SP ones (<0.1 µm) mobilize together with water via porous media and are influenced by physicochemical processes occurring in soil profile (Mohammadnia and Kowsar, 2003).

Furthermore, soil compaction is another type of physical clogging, which mostly occurs on the surface of a recharge system due to excess water. Theoretically, there is a linear relationship between the water level of recharge basin and the recharge rate. However, because of unavoidable particle deposition and algal growth on the surface of the seeping zone, unreasonably increase in water level and decrease in recharge rate might occur simultaneously due to the compaction of clogging layers (Huang, 1993).

In a recharge basin system, finer-grained soils are more prone to clogging process than coarser-grained ones because small pores can easily be blocked by SS. Microbial growth (biofilm) on soil particles can result in significant reduction in effective porosity and, hence, affecting the infiltration capacity. In addition, downward migration, and near-surface accumulation of small-sized (clay sized or smaller) particles driven by the seepage force result in the formation of confining layer, which is known as micro-clogging. This phenomenon is a determining factor for the formation of crust in soil (Bouwer, 2002). In addition, dissolved impurities may convert to suspended ones during well injection due to physico-chemical changes of the recharging water. For example, minute quantities of Fe and Mn in the water may fluctuate/ fall by flocculating or precipitating with CO_3; or influenced by the changes in pH and Eh, the clogging can occur again by those impurities present as SS.

3.2 Clogging caused by mobilization of fine particles in the aquifer

Most of previous researches have focused on suspended particles present in the injection water (Ahfir et al. 2009). The study of clogging due to mobilization of small particles is limited because of its complexity. This type of clogging is primarily dependent on infiltrating velocity or the hydraulic gradient. Moghadasi et al. (2004) studied the mobilization of fine particles during well injection in an aquifer by using a glass packed with particles of alumina to estimate the effect of injection rate on the movement of alumina particles in the aquifer. The study indicated that after a certain time, a rapid drop in hydraulic pressure during the injection process resulted in plugging of the pores due to the mobilization of the particles. After a while, the clog broke and the larger flow path occurred and the hydraulic head drop decreased. This result suggests that, to estimate physical clogging due to particle mobilization, a critical hydraulic gradient (i_c) or critical velocity (V_p) should be estimated. This can be determined by considering the piping effect of earth embankments. Different studies on i_c or V_p have been reported earlier in the literature (Jones, 2010). A critical hydraulic gradient (i_c) describes that when the effective stress reaches near zero value in a testing medium for water flowing, then $i \times \gamma w$ (flow pressure) is almost like submerged/ inundated (buoyant) mass of soil on unit basis (Terzaghi et al. 1996). Ohno et al. (1984) proposed an empirical formula for critical velocity ($V_p= 2.25d^{1.94}$, where V_p is critical velocity in cm/s and d is size of particle in mm).

3.3 Clogging by gas bubbling

Gas bubbling that often causes clogging can happen due to two processes, i.e. entrapment of air and biogenically formed gasses (Holocher et al. 2003). The former occurs due to the rise in water table during the artificial recharge processes (Martin, 2013). The latter can be attributed to the production of biogenic gases (H_2S, CO_2, CH_4, N_2) because of microbial respiration (Heilweil et al. 2009; Beckwith and Baird, 2001). The both can account for the blockage of 7-20% pore spaces (Beckwith and Baird, 2001; Heilweil et al. 2004), which usually clogs the throat of large pores and reduces the aquifer permeability (Hoon et al. 2017).

4 Chemical clogging

Precipitation and dissolution of certain chemical species or minerals such as sulphates, phosphates, calcium carbonates etc. result in chemical clogging; and these reactions are mostly catalyzed by microbes. The precipitated products with the involvement of metal bacteria which cause chemical clogging include $Fe(OH)_3$, $FeH_2(CO_3)_2$, Mn, metallic sulfide (S^{2-}), or $CaCO_3$ of saline water (having high Na) reacting with soils result in swelling and de-flocculation of clay-sized particles. Before artificial recharge, groundwater is generally considered constant in terms of qualitative and safety aspects. However, it differs remarkably in composition as affected by a myriad of complicated factors/parameters after the recharge. These parameters include infiltrating water quality, interactive process with the percolated soil horizons, redox potential, environmental (temperature) conditions and bacterial activities. Geochemistry incompatibility between the recharging water and original GW and mineralogical properties of aquifer substances leads to the presence of different precipitates derived from the products of chemical reaction. Chemical precipitation due to elusive chemistry of certain ions such as iron (Fe) and manganese (Mn) are extremely important in chemical clogging. As the earth's crust comprises about 5% Fe and 0.1% Mn, therefore, these ionic species wildly distribute in both surface water and groundwater. During weathering of igneous and sedimentary rocks and water circulation in rocks and soils, leaching and dissolution of these ionic species in GW takes place. The N compounds such as NO_3, NO_2 and NH_3 are generally considered as indicative parameters for potential pollution due to animal wastes and domestic sewage in saturated zone (phreatic) GW (WHO, 2008). In groundwater with anoxic conditions, decomposed organic matter (OM) defines the production and nature of inorganic compounds (De Vet, 2011). The OM decomposition under oxidized environment augments not only the content of NH_4^+ but also other substances of inorganic nature such as Fe, Mn and trace elements are generated by dissolved soil minerals due to reductive-dissolution process. Fe and Mn usually exist in their divalent soluble forms under a reduction environment with less dissolved oxygen and low pH, but this condition is often changed, which causes the redox reaction of the dissolved species in groundwater. For example, there are mainly two species of iron i.e. ferrous iron (Fe^{2+}) and ferric iron (Fe^{3+}). Ferrous iron can become ferric iron by oxidation; and the former has a high solubility than the latter which is 2.0×10^{-39} at 25°C for Fe^{3+} hydroxide (Jones and Atkins, 2000). This is why the Fe hydroxide [$Fe(OH)_3$] easily precipitates on the surface in the forms of iron coatings and flakes which are mostly visible in the water, appearing in an undesirable color and an unfavorable smell (Fig. 2d-Fig. 2f). The redox reaction for iron is represented below:

$$\text{Reduction reaction}: O_2+4H^++4e^-=2H_2O \tag{1}$$

$$\text{Oxidation reaction}: 4Fe^{2+}=4Fe^{3+}+4e^- \tag{2}$$

$$\text{Redox reaction}: O_2+4Fe^{2+}+4H^+=4Fe^{3+}+2H_2O \tag{3}$$

Formation of Fe-hydroxide [$Fe(OH)_3$] due to conversion of Fe^{2+} to Fe^{3+} is represented as follows:

$$4Fe^{2+}+O_2+2H_2O \leftrightarrows 4Fe^{3+}+4OH^- \tag{4}$$

$$4Fe^{3+}+4OH^-+8H_2O \leftrightarrows Fe(OH)_3+8H^+ \tag{5}$$

$$4Fe^{3+}+4OH^-+10H_2O \leftrightarrows 4Fe(OH)_3\downarrow+8H^+ \tag{6}$$

Similarly, the redox reaction for Mn in a simplified form is represented below:

$$\text{Reduction reaction}: O_2+4H^++4e^-=2H_2O \tag{7}$$

$$\text{Oxidation reaction}: 2Mn^{2+}+4H_2O=2MnO_2+8H^++4e^- \tag{8}$$

$$\text{Redox reaction}: O_2+2Mn^{2+}+4H^++2H_2O=2MnO_2+8H^+ \tag{9}$$

The partially oxidized and low crystalline intermediates of Fe (Fe^{2+}, Fe^{3+}) followed by stable crystalline Fe^{3+} (hydro)oxides (e.g. goethite) are end products of these reactions. In addition, reduced minerals such as magnetite (Fe_3O_4), troilite (FeS) and marcasite (FeS_2) can be formed during well casing corrosion (Martin, 2013; Hoon et al. 2017). The pH and pε are influencing factors for these redox reactions occurring in soil and water systems. There is an inverse relationship between the solubility of Fe^{2+} and Mn^{2+} and pε (Stumm and Morgan, 1996). Generally, the concentration of Mn (as [Mn]) is less than 1 mg/L; at times it can reach as high as 5 mg/L and at an intermittent state this value could be much higher. In most wells, the concentration of iron (as [Fe]) is less than 5 mg/L and [Fe] value can range from less than 1 mg/L to above 40 mg/L (John and Harold, 1983). Fe and Mn may also exist in other forms. The complexes of either an organic nature (organic molecules such as organic acids (humic, fulvic or tannic acids) impounded the element by providing a protective layer/shell that resists its removal from the shell) or mineral nature (complex forms in the presence of naturally occurring silicates, phosphates, or polyphosphates) may occur with both elements. Dissolution from geological formations and decomposition of organics may release Fe and Mn in surface-based water systems, e.g. O_2 free environment induced Fe and Mn dissolution from reservoir bottom sediments followed by the distribution of the elements in the entire water supply due to the presence of temperature gradient over seasons. The presence of Fe in O_2 saturated surface water with pH of around 7 is largely in the form of oxidized state, i.e. the insoluble iron hydro-oxides. Both Fe and Mn may also exist as a complex due to presence of organic acids. Mn is present as soluble Mn or insoluble Mn in surface water, depending on the ambient environmental conditions. Nevertheless, Fe mostly exists as Fe^{3+} (oxidized) state, while Mn may exist as a reduced state because rigorous oxidizing environments are required to oxidize the reduced (soluble) form to the oxidized (insoluble) one and these conditions particularly prevail in surface water. Due to the oxidation and precipitation capacity under different environments, Fe and Mn may be problematic due to their presence as insoluble oxides, resulting in visual and reactive water issues. Even a minute Fe concentration may cause the environment conducive for iron related bacterial species to grow and use the energy when Fe^{2+} is oxidized to Fe^{3+} during fixation of dissolved CO_2 into organic molecules as a perquisite for their life cycle. A gelatinous mat is formed because of the microbial growth at a reasonable rate, which can result in pipe encrustation and corrosion due to the formations of galvanic cells and corrosive by-products (e.g. H_2SO_4 and H_2S) from related microorganisms (John and Harold, 1983).

During water injection, two types of scale formation can occur due to the changes in temperature, pressure, and pH of the injected fluid. These scales are termed as calcite ($CaCO_3$) and gypsum ($CaSO_4$) based scale formations. Furthermore, iron-induced complex scales i.e. ferrous hydroxide

(Fe(COH$_2$), trollite (FeS), magnetite (Fe_3O_4) and marcasites (FeS_2) are formed together with the occurrence of downhole corrosion. Sulphate based scales are insoluble in acid while carbonate-based scales are acidly soluble. Therefore, sulphate-based scales are difficult to remove by using conventional methods other than mechanical penetration (Bennion et al. 1998; Martin, 2013). Excessive scaling is disruptive in water transfer and penetration. Apart from these hardness-causing ions, different cations (sodium, potassium, iron) and anions (nitrate, chloride, sulfate, bicarbonate) may be present in water. Different indices for corrosion and scale forming include the Langelier saturation index (LSI), Ryznar stability index (RSI), aggressive index, Puckorius scaling index (PSI), Larson-Skold index (LR) and Aggressive index (AI). The use of different indices indicates that there is no single solution for determination of water corrosion and scale-forming.

Different mechanisms and environmental conditions influence the dissolution of these elements and also affect their concentrations and chemical states in the water. For example, the Fe presents in GW will precipitate when the mixed GW with recharging water has the pH and Eh values within the range for Fe^{3+} formation. The Eh of the recharging water greatly differs from that of local GW in the aquifer. In humid regions with a high amount of organic compound, the O_2 contents and Eh values are much higher than that of arid regions; as a result, the O_2 used in oxidative process in arid areas might be used in a reduced environment in shallow parts of humid areas. Dissolved oxygen (DO) is considered a reliable parameter obtained from the field test for both GW and surface waters, whereas, Eh is the most reliable parameter for GW, especially the GW with low concentrations (<0.1 mg/L) of Fe and Mn. In ARS, normally the surface recharging water is O_2-saturated, while the GW is mostly less O_2-saturated, or even anaerobic in the deeper parts of an aquifer. The most important reaction involved is the mixing of anaerobic GW having Fe^{2+} with aerobic (O_2) recharging water, forming insoluble Fe^{3+}-hydrates. Reduced forms of cations such as Fe and Mn present as hydrochemically active species as well as reduced N and S compounds will be prevalent. As described above, possible precipitation of Fe and Mn oxides or hydroxides during the recharge processed in the well is proportional to the change in dissolved O_2 levels, and $CaCO_3$ chemistry (solution or precipitation) with respect to changes in reaction (pH) and CO_2 levels. The mechanisms of clogging due to chemical processes are hence complicated and diverse which are dependent on different factors such as hydrogeochemistry of recharging water and the GW, composition of the aquifer involved as well as and eco-environmental factors like temperature, pressure, etc. That is because they affect the processes of precipitation and deposition. Mostly, these reactions are bacterially mediated; hence, uncoupling of biological and chemical clogging processes is quite difficult. There is a linear relationship between precipitation or dissolution rate and mineral' s reactive surface area. Furthermore, metabolic processes of bacteria, flux of gases (↑ and ↓ of O_2 and CO_2), and existence of catalytic reactions might also have an impact on the subjected mineral precipitation and dissolution (Pérez-Paricio, 2001). In abstracting wells and during iron hydroxide precipitation, three oxidation processes, i.e. homogenous, heterogeneous, and biological oxidation processes are active. Homogenous oxidation (mixing of Fe^{2+} and oxygen, and precipitation of Fe^{3+}-hydroxides) process rate is directly proportional to the increase of pH value, and oxygen and Fe^{2+} concentrations. In heterogeneous oxidation (adsorption of dissolved Fe^{2+} on the above precipitates and subsequent oxidation and hydrolysis of adsorbed Fe^{2+}), the adsorption process rate is limiting and fast in neutral conditions. This rate is directly proportional to the increase of pH, $[Fe^{2+}]$ and $[Fe^{3+}]$ and the increase of Fe^{3+}-hydroxide surface area (Van Beek, 2010). In the presence of iron oxidizing bacteria (IOB), biological oxidation (adsorption of dissolved Fe^{2+} on bacterial cell walls and on their extracellular polymeric substances, and subsequent oxidation and hydrolysis of adsorbed Fe^{2+}) will take place. This shows that there might be a fierce competition between heterogeneous and biological adsorptions of the dissolved Fe^{2+}, if both IOB and Fe^{3+}-hydroxide precipitates are present (Van Beek, 2010). The screen slot (chemical) clogging of abstraction well is caused by the accumulation of chemical precipitates, whether or not accompanied by the activity of biomass. These precipitates consist usually of iron hydroxides with all kinds of admixtures, like phosphate, manganese, and trace elements, and in the biomass iron oxidizing bacteria like Gallionella ferruginea and Lepthotrix ochracea are easy to be recognized. Houben (2006) reported that the occurrence of Fe hydroxide precipitates in the gravel pack was in agreement with information obtained from excavated wells (Houben and Treskatis, 2007), which showed the gravel pack was completely cemented by Fe hydroxides, but not the adjacent aquifer. However, it was not clear whether this gravel pack was cemented completely over its whole length or only part of that.

5 Biological clogging

The biological clogging or bioclogging occurs in natural porous media under a wide range of conditions is mostly in combination with physical or chemical clogging. In this clogging process, bacterial cells first adhere to solid particles, then cellular growth occurs with time and ultimately develops over the entire deposit as a biofilm as outlined in Fig. 2c. According to Camprovin et al. (2017), there are five stages of bioclogging processes during the biofilm formation based on extracellular polymeric substances, i.e. (i) attachment, (ii) cell-cell adhesion, (iii) proliferation, (iv) biofilm maturation, and (v) detachment. Biological clogging is problematic in different areas such as artificial recharge of GW, in situ aquifer cleanup (bioremediation) from contaminants, wastewater disposal, secondary oil recovery and construction of water reservoirs, etc. All these processes are affected by this type of clogging (Baveye et al. 1998). Bioclogging of porous medium is due to bioaccumulation of related microbes, which may result in the reduction of porosity and hydraulic conductivity of the medium (Thullner, 2008). Baveye et al. (1998) documented four possible microbe-induced clogging processes (i) bioaccumulation in porous medium with microbial cellular entities, (ii) exudation of microbial extracellular polymeric (chiefly polysaccharides) products, (iii) generation followed by the trap of different gas products, e.g. CO_2 (respiratory products), N (denitrification products), and CH_4 (methanogenesis products), and (iv) microbial-induced precipitate accumulation with very low solubility. The possible influencing factors for bioclogging include concentrations of dissolved OC, OM, total NO_3, total P and temperature. In contrast to physical clogging, biocloging development rate is slow and it takes a longer time (several days to several weeks) for the clogging to appear after the beginning of recharge process (Rinck-Pfeiffer et al. 2000). Seki et al. (1998) reported that the permeability of the seeping media decreased quickly in the beginning few days and then the decrease slowed down after that. The biofilm forms on the aquifer medium decrease the pore spaces to a considerable extent that may ultimately result in temporal blockage of artificial recharge facilities. Schmidt et al. (2007) reported that the addition of oxygenated water to the system can induce a favorable environment to enhance bacterial activity, which can produce biofilms and clog well screens.

Among microbial community, bacteria and algae are the main microorganisms responsible for bioclogging that ultimately reduce the seeping media’s hydraulic conductivity, of which the case of algal clogging has relatively less been documented than that of bacterial clogging because the latter plays a more important role in bioclogging. However, clogging caused by algal growth can be very severe, especially in surface recharge systems. Goodrich et al. (1990) reported that algal bloom is more predominant in the upper portion of the surface, especially within the upper 7.5 cm layer. For catalytic reactions, bacterial cells require exogenous electron acceptors, and for synthetic process cells need organic-C in the case of heterotrophic bacteria and inorganic-C in the case of autotrophic bacteria (Pérez-Paricio, 2001). O_2 is the first available choice and highly effectual electron acceptor for the synthesis of energy because it is a vital factor for growth of bacteria. Iron and sulfate reducing bacteria are a natural part of the environment and may enter the aquifer through wells or other interactions. Well clogging phenomena is primarily attributed to Fe-bacteria (Gallionella, Thiobacillus, Sphaerotilus and Leptothrix sp.) induced biofilm generated in the groundwater due to O_2 dynamics during pumping process that can result in anaerobic conditions from aerobic conditions (Gino et al. 2010). In comparison with the effluents, bacterial community in the wells is less diversified that might be ascribed to fewer organics and, more metallic ionic species (Fe^{2+} and Mn^{2+}) in the GW and significant variations in O_2 supply (oxic/anoxic environment). Hence, if exogenous pollution problem in the AR system is negligible, then only specified bacterial species (e.g. Fe- and Mn- oxidizers/reducer and SO_4-reducing bacterial strains) will be predominant in operational wells (Gino et al. 2010). The wells with groundwater containing high [Fe^{2+}] will be severally clogged because of the biotic Fe-oxidative process. Iron bacteria use iron in their metabolism and grow best in water with high iron content. Under suitable or moderate conditions, they grow, multiply, reproduce, and tend to colonize on the well and pump surfaces, causing slimes, and depositing iron oxide on the surfaces or producing corrosive acids. Bacteria can also produce certain amount of gases such as N_2, CH_4, CO_2 that can considerably clog the soil pores. Many bacterial strains might substitute nitrates for oxygen as an electron acceptor during metabolism.

Therefore, these strains are able to grow under a wide range of aerobic or anaerobic environments. Sulfate bacteria reduce sulfates, usually under anaerobic and reducing conditions, to obtain energy for their metabolism. Corrosive hydrogen sulfide is a byproduct of their metabolism.

The bulk masses of brown gelatinous substances possessing stickiness properties are produced by Fe-bacteria. Generally, bacterial growth occurs by releasing certain enzymatic substances involved in catalyzing or promotion of Fe related chemical reactions within GW. Bacteria utilize energy as a byproduct of these chemical reactions (by oxidizing Fe^{2+} or less frequently available manganese), grow and multiply. The resulting product in the form of ferric oxide appears as a brown gelatinous slime. As described earlier, common bacterial species known to feed on Fe are Thiobacillus ferrooxidans and Leptospirillum ferrooxidans. These iron bacteria convert Fe^{2+} to Fe^{3+}. The precipitation of Fe^{3+}-hydroxides by Fe^{2+} and oxygen produces energy that may be utilized by the micro-organisms. This energy production reaction can be represented as below:

$$Fe^{2+} + H + 1/4H_2O \rightarrow Fe^{3+} + 1/2H_2O + xKJ/mol \tag{10}$$

Then, reaction between ferric iron (Fe^{3+}) and H_2O results in the formation of insoluble iron hydrooxide [$Fe(OH)_3$] as below:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3\downarrow + 3H^{+} + yKJ/mol \tag{11}$$

Fresh Fe^{3+}-hydroxide precipitates in clogging wells consist mainly of hydrous ferric oxide (HFO), and older precipitates of goethite. Sometimes, Lepidocrocite occurs as a minor constituent, while the presence of hematite has never been reported (Houben and Treskatis, 2007). These iron oxidizing bacteria (IOB) can utilize energy produced by oxidation and precipitation for their metabolism (Emerson and Weiss, 2004; Kappler and Straub, 2005). Because the precipitation of Fe^{3+}-hydroxides from Fe^{2+} and oxygen only produces little energy, the IOB need to convert large quantities of Fe^{2+} to meet their energy requirements. This is only possible where both oxygen and Fe^{2+} are present. For that reason, IOB are typical representatives for oxygen–Fe^{2+} interfaces (Emerson and Weiss, 2004), characterized by variable Fe^{2+} but low oxygen concentrations, and slightly an acidic to neutral pH ($5.5 <$ pH < 7.5) conditions (Van Beek, 2010). Mn can also form insoluble precipitates with similar chemical reactions. Briefly, bacteria can cause clogging by (i) bacterial mass, (ii) insoluble Fe- and Mn-hydroxides, and (iii) adhesion of sticky gelatinous bacterial mass to small sized sediment particles. Influencing environmental factors are (i) dissolved Fe (Fe^{2+}) ion source, (ii) O_2, and (iii) optimum pH. As microbial clogging evolves in time and space, hence, redox conditions, metabolic nature of bacterial community, and stage of soil anaerobiosis are important influencing factors, especially in the surface systems. Higher the redox potential of a system, lower the electrons activity, greater the potential for accepting or transferring electrons, greater the capacity of an oxidant for reduction, and higher the free energy release during the redox reactions. Chemoorganotrophic bacteria meet their energy requirements by oxidizing organic molecules and by using a diverse array of oxidants for the oxidation of OM. Among them, O_2, NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} are most important oxidants. The commencement of reduction process of different oxidizing agents (NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}, and CO_2) present in soil pursues thermodynamic principle, which describes that, to obtain the maximum free energy, the reduction of available stronger oxidants in a system will be carried out by a given electron donor/reluctant. Thus, those reactions/processes (e.g. aerobic respiration or denitrification) that can produce maximum energy will be carried out first and those reactions/processes (e.g. SO_4-reduction or methanogenesis) that produce less amount of energy will be carried out at later stages (Baveye et al. 1998). In many real situations, uncoupling of chemical and biological clogging processes/mechanisms is quite difficult and hard to distinguish these two processes.

6 Preventive measures and redevelopment methods

As outlined in Fig. 3, an integrated strategy is needed to minimize the clogging problem in artificial recharge systems. The best control strategy for clogging is its prevention, i.e. influencing parameters and factors causing clogging should be controlled or minimized. Irrespective of the up-to-date redevelopment methods/techniques, prevention remained the best approach (Pérez-Paricio, 2001). However, depending upon the recharge facility, water quality and hydrogeochemistry, after certain recharge period, it is necessary to deploy a redevelopment method.

The preferable option for clogging prevention is that we should try to control the quality of water. In this context, prime factors are the quality and SS present in recharging water that define the main criteria for infiltration in surface water recharge as well as for injection by borehole systems. Other

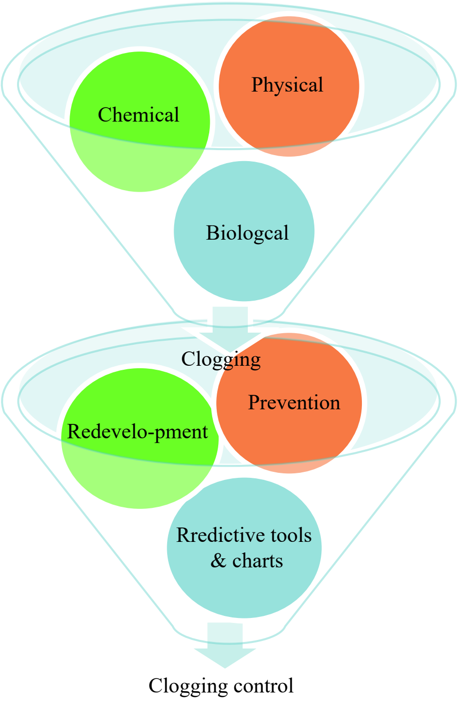

Fig. 3 Integrated strategy to minimize clogging problem in artificial groundwater recharge systems

influencing factors are pH, OC contents and nutrients. Processes of gas formation or air entrapment should be minimized during injection in ARS. In case of wastewater reuse for artificial recharge, clogging issues can be avoided/ minimized by optimum filtrating process, addition of chelating agents and disinfection of the wastewater before injection. Parimalarenganayak (2021) reported that using excess desalinated water or treated sewage effluent was most widely applicable technique for aquifer storage and recovery in Gulf countries. The hydraulic conductivity of aquifer can be enhanced by increasing the dissolution of $CaCO_3$ minerals, especially in those with high sodium (saline) contents (Saharawat et al. 2011). However, Bouwer (1999) reported that effluents' recharging the wells need to be treated with improved treatment techniques such as (i) N and P-elimination, (ii) filtrating process for sand, (iii) alleviation of SS and removal of parasites (e.g. helminths, Giardia and Cryptosporidium), (iv) disinfection treatment for microbes (viruses and bacteria), and (v) reverse osmosis techniques to mitigate organic substances and chemicals. Some engineering methods for prevention and redevelopment purposes used in artificial recharge systems are enlisted in Table 2.

In the surface systems, clogging rates are directly proportional to infiltrating capacity due to enhanced surface loading capacity for SS, nutrients, and OC. As a result, injecting pressures in the recharging wells are increased, showing that the clogging signs can speed up the clogging process. Bouwer (1999) reported that periodic redevelopment and regular pumping of the recharging wells can slow and even mitigate the clogging process in a short time. He also reported that an early clogging detection followed by the application of controlling measure is a successful and reliable preventive measure for biofouling, otherwise its efficiency is questionable at the latter stage. To minimize the clogging, recurrent recharge cycles are basically necessary for the surface ARS, whereas back flushing is more important in the deep system. Direct injection recharge wells are needed to have a better infiltration to the confined or deep aquifer system with low permeability topsoil and unfavorable vadose zone. Moreover, these injection wells require rehabilitation, for which associated approaches to restoring the clogged well are shown in Fig. 4.

Shifting of impurities from dissolved to suspended states during well injection process can take place due to the change in recharging water physico-chemical environment. As described above the variation of CO_2, pH and Eh can result in the precipitation of Fe and Mn that can lead to clogging caused by impurities present as suspended forms. Clogging due to SS might be removed by well cleaning but might not be effective for complete removal. There are different cleaning techniques toward clogging, based on physicochemical properties of the involved aquifer and clogged wells, such as acidizing the well under pressure, applying the heat and shockwave, percussion instruments and methods for fluid, combining spurted disinfectants, detergents and heat waves (32°C to 100°C, at 51 Atm), applying disinfectants (Cl, H_2O_2, Br-compounds, chelating organic acids), CO_2, P-based acids, polymeric substances, and different blending/combinations of above stated protocols tested in field studies represented variable results (Gino et al. 2010; Smith and Comeskey, 2009).

Geothermal heat pump systems are used to harness the heat/thermal energy captured in upper parts of the earth crust and can be categorized into an open loop and closed systems (Fig. 5). In these systems, groundwater or carrier fluid with absorbed heat is connected to the heat pumps from where the heat energy can be distributed for heating or cooling engineering structures. In a closed system, a heat transfer fluid (refrigerant) transfers the captured heat to a heat pump by circulating in

Table 2 Preventive measures and redevelopment methods in artificial recharge systems

Types	Approach	Methods
Physical	Prevention	(1) Coagulation (coagulants like alum and organic polymers in surface system), flocculation, precipitation, and filtration (sand or membrane filters for well recharge) to remove particles, (2) Pre-sedimentation to settle clay, silt and other suspended solids in surface system, (3) For injection wells and deep systems, periodic pumping and backwashing, (4) For surface infiltration systems-recharge cycle approach i.e. alternative/periodic use and drying (letting the clogging layer dry, decompose, shrink, crack, and curl up) followed by mechanical removing, disking, crust breaking, plowing of clogging layers, smoothing, lightly soil compacting by rolling or dragging etc. (5) In soil compaction of surface system, limit the recharge water height/depth.
	Redevelopment	(1) In deep systems, pumping, high pressure jetting chemicals (disinfectants and acids), fluid based methods, and recharge protocols, (2) In surface systems, during operations, filtration (mats, filters), enhance natural factors (aeration, avoid light), and other methods like underwater robot to scrap clogging layer, (3) In surface systems, between operations, mechanical methods (tillage, scraping), natural methods (basin drying & freezing) etc.
Chemical	Prevention	(1) Acidification, (2) Daily pumping, (3) Separate strata, (4) Avoid oxygen, (5) In case of gas generation, recharge water having temperature > groundwater temperature.
	Redevelopment	(1) In deep systems (i) use of specific chemicals e.g. chlorine, acids and polyphosphates etc. (ii) hydro-mechanical methods, and (iii) TV surveys and scrapping borehole wells by brushing etc. (2) In surface systems (i) use of chemicals (calcium based) during operations, and (ii) acid baths to remove carbonated deposits between operations.
Biological	Prevention	1. For bacteria: (i) Disinfection (chlorine and other disinfectants), (ii) Reduction of nutrients, (iii) Limit input concentration (reduction of organic carbon level by using activated carbon filtration and/or reverse osmosis or other membrane filtration), (iv) Oxidizers, (v) Acidifiers. 2. For algae (surface systems): (i) Filtration, (ii) Reduction of nutrients (P and N), (iii) Chemicals, (iv) Avoid direct sun light.
	Redevelopment	(1) In deep systems, for bioclogging (i) pumping, (ii) chemicals, (iii) mechanical/physically based methods, (iv) combination of methods.
Generic	Prevention	(1) Appropriate water treatment, (2) Minimize aeration (wells), (3) proper lay out and designing, (4) Install high water alarms.
	Redevelopment	(1) Flow reversal pumping promote detachment, (2) Dosing of specific chemicals (disinfectants, acids), (3) Fluid based injection methods, (4) Adoption of recharge protocols.

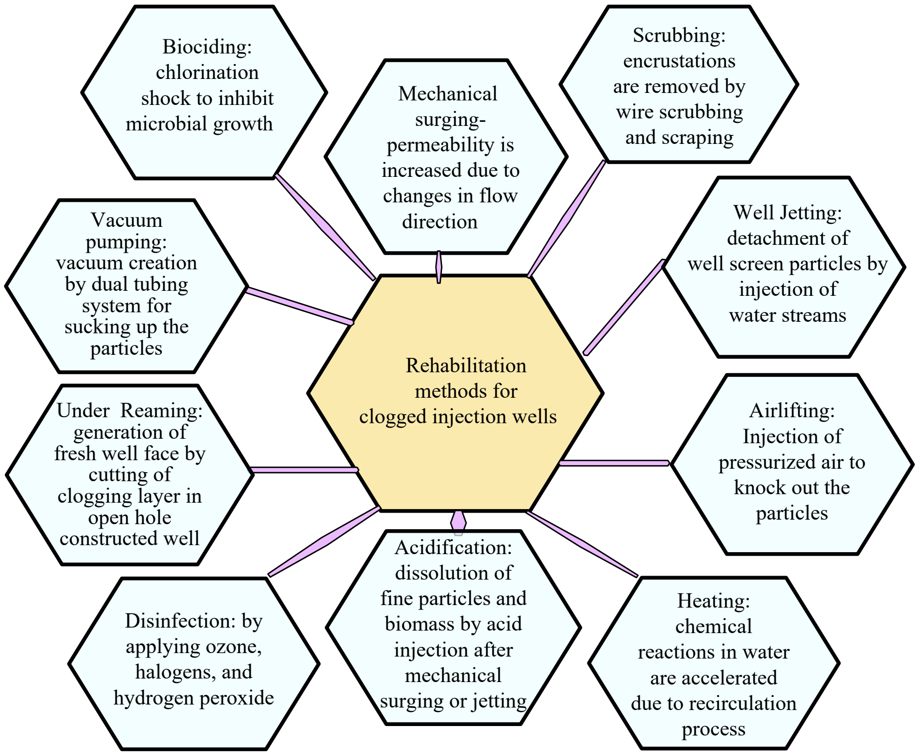

Fig. 4 Rehabilitation approaches for restoration of injection wells with clogged aquifers (Martin, 2013; Hoon et al. 2017)

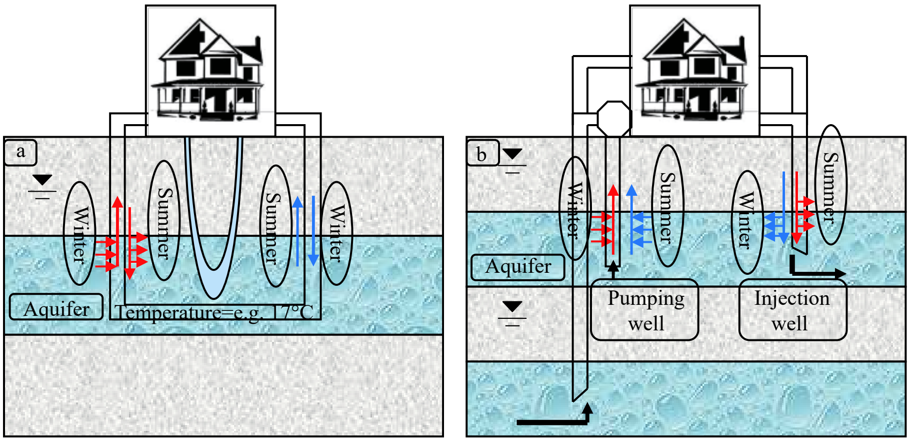

Fig. 5 Schematic layout for (a) vertically closed and (b) open loop heat pump systems depicting the cooling mode in summer and heating mode in winter seasons for different engineering structures

horizontally or vertically oriented and high density polyethylene pipes and the range of borehole depth is between 30 m and 100 m (Zeng et al. 2003; Hecht-Mèndez et al. 2013). In an open system, extracted groundwater acts as a carrier fluid for thermal energy. To exploit the groundwater heat energy, a closed system might be considered better than the open one because the former is less prone to clogging. Therefore, closed system might be a better choice than the open one in terms of operational and maintenance cost to mitigate clogging, whereas the open system is more efficient t in terms of the geothermal energy utilization.

Bacterial growth can be restricted by (i) using sand or other material filters to remove as more organics as possible from the recharge water before it is injected, and (ii) chlorine shock-bacteria elimination with Cl (by keeping a residual concentration of 1-2 ppm). In the surface water treated with Cl, elevation of Eh and dissolution of O_2 might play a significant role in controlling the microbial communities which are originated from soil horizons and are proliferated in GW. Although the sterilization of recharging water is done with Cl, microorganisms are extremely active in the aquifer to enhance microbial mediated processes or reactions. These include nitrification-denitrification reactions, and SO_4, Fe, and Mn reducing processes during the mixing of recharging water with GW. It is extremely difficult to amend the subsurface oxidation-reduction capacity; however, compounds influencing the changes in subsurface hydrogeochemical reactions can be removed. By doing so, compatibility between recharging water and ambient GW can be improved.

Clay particles can swell and soil porosity can reduce in an aquifer because of the reduction in ratio of Ca^{2+}+Mg^{+} to Na^{+}+K^{+} or lowering of ionic strength values. Ye et al. (2019) investigated kaolinite particle clogging in porous media and reported that hydrochemistry–related clogging was enhanced because of the chemical flocculation which increased the deposition rate by 1-2 times in a high ionic strength condition. This can be avoided by selecting different kind of recharging water or by adding $CaCl_2$ to the recharging water or pre-flushing with water having high content of $CaCl_2$. To minimize clogging, some recommendations for recharge water quality and basic parameters for clogging prevention and redevelopment in the deep and surface recharge systems obtained from pertinent literature after Pérez-Paricio and Carrera (1999) are depicted in Table 3. These parametric values are threshold levels that can be considered as a basic guideline, but these values might be the aquifer and site specific. To estimate the clogging intensity, simplified criterion is designed, based on some simple parametric indicators. However, the other influencing factors such as temperature, hydraulic conductivity, recharge regime, light, and certain nutrients etc. need to be further included to achieve a more comprehensive criterion act as the guideline/recommendation to minimize the well clogging problems. For example, Saman et al. (2021) proposed a new hybrid framework of site selection for ASR in arid and semi-arid regions by employing the AHP decision-making model with the parameters as hydraulic conductivity, specific yield, slope, land use, depth to groundwater and aquifer thickness. Furthermore, inter-dependence and coupling effects of clogging mechanisms are a real challenge in many practical fields that requires additional parameters to be included for the development of clogging mitigation guidelines.

Generally, there are many methods available for

Table 3 Recommended values of recharge water quality and basic parameters for clogging prevention and redevelopment in deep and surface recharge systems

Recommended basic parametric values			**Simplified guidelines/Criterion for clogging**		
Clogging types		**Recommended values**	**Clogging intensity**	**Parametric values**	**Redevelopment**
Physical	Well injection (deep systems)	[1]TSS<2 mg/L when (K>40 m/d), [1,2,9]TSS<0.1 mg/L when (4m/d<K<40 m/d), [3]MFI<3-5 s/L^2, [2,4,9]Turbidity<1 NTU	Deep Systems	TSS<10 mg/L, Turbidity<5 NTU, TOC<10 mg/L	Frequent pumping, Monthly surging/jetting
	Surface recharge (surface system)	TSS<10 mg/L, Turbidity <5 NTU		TSS = 10-20 mg/L, TOC = 10-25 mg/L	Daily pumping, Weekly surging/jetting
Chemical		[5]$[\mathrm{Fe}^{2+}]$<11.2 mg/L, [6]pH<7.5, [6]low $[\mathrm{Ca}^{2+}][\mathrm{Mg}^{2+}]$, [6]TDS<150 mg/L, [6]$[\mathrm{Cl}^{-}]$ <500 mg/L [6]Ryznar index>7 [7]Saturation index of mineral	Increased	TSS>20 mg/L, TOC>25 mg/L	Daily pumping, Adapted protocol
			Surface systems	TSS<10 mg/L, Turbidity<5 NTU, TOC<10 mg/L	Natural drying & cracking, Annually-mechanical
Biological	Well injection (deep systems)	[8]pH>7.2, [8]Avoid CO_2, [8,9]DOC<2 mg/L, [8]Eh>10 mV		TSS = 10-20 mg/L, TOC = 10-25 mg/L	Frequent drying and cracking, Biannually-mechanical
	Surface recharge (surface system)	Increased	TOC<10 mg/L	TSS>20 mg/L, TOC>25 mg/L	Pre-filtration

Note: [1]Pyne (1995); [2]Dutch standards (Peters, pers. Comm.); [3]Olsthoorn (1995); [4]German standards (Schöttler, pers. Comm.); [5]Lucas et al. (1995); [6]Ford (1990); [7]Hills et al. (1989); [8]Degalier (1987); [9]Stuyfzand et al. (2005)

Fe and Mn alleviation, apart from ion-exchange process. Although, various methods, such as membrane based filtrating process, oxidation-reduction processes, chemical based precipitation processes, sorption, ion exchange, reversely osmotic processes and others, are available for metal removal from groundwater, most of them are quite expensive to apply and fail to provide a cost-effective strategy, and difficulty exists in its procurement in developing countries. Therefore, there is a dire need to explore or redesign inexpensive and eco-friendly methods/techniques/strategies for the removal of metals such as Fe and Mn from the groundwater. Diverse biosorbents, e.g. environmentally safe and agro-industrial wastes and raw materials like saw dust, hull and husk of paddy rice and wooden charcoal have gained popularity as alternative biosorbents (Pino et al. 2006; Mahvi et al. 2008). For example, sand and pebble filter has been applied in purifying groundwater for more than >200 years due to its simplicity, economics, easiness in operational and maintenance by using native materials. Efforts are in progress for development of cheaper activated C sorbent by using alternative raw materials for alleviating metallic ions. Presently, we tested different materials (bamboo charcoal, oyster and scallop shells, sand, slag, volcanic ash, and standard sand etc.) to estimate their relative filtering potential for Fe and Mn removal from groundwater in the short- and long-term column experiments. From these experiments, we found that bamboo charcoal was very effective in the removal of iron from groundwater. This could be an eco-friendly and low-cost process by deploying the waste material of bamboo firewood which can be easily made and prepared. We investigated in laboratory experiments that tested charcoal has an adsorption capacity of 3.5 g iron kg^{-1} of charcoal (Ruemenapp et al. 2013). Similarly, in another study, we compared three different filter materials (wooden charcoal, filter sand and volcanic ash) and found that wooden charcoal has more effective retention capability, compared to the other two (Fig. 6-Fig. 8). In one field study conducted in Japan, we tested charcoal filter in an open loop of groundwater heat pump system (Fig. 9). Although charcoal filter proved to be very effective in removing dissolved Fe from the injected water, further field tests are needed to validate the efficiency of these kinds of materials used on a sustainable basis. These types of low-cost and eco-friendly strategies will provide more practical and applicable solutions, especially in resource limited countries.

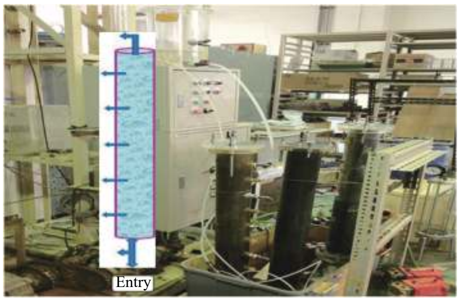

Fig. 6 Experimental setup to test charcoal (size 2-4 mm) potential to remove iron from groundwater in upward flow mode

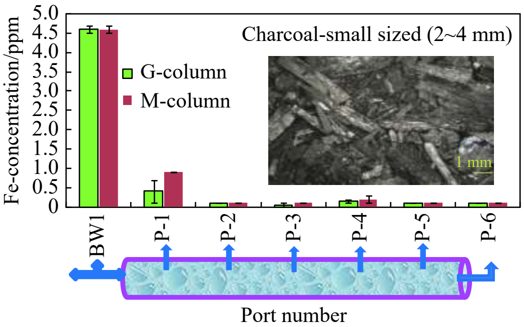

Fig. 7 Fe-concentrations in effluents from different ports (P1-P6) and in blank groundwater (BW1) after 6 days in a column experiment with upward flow mode of groundwater

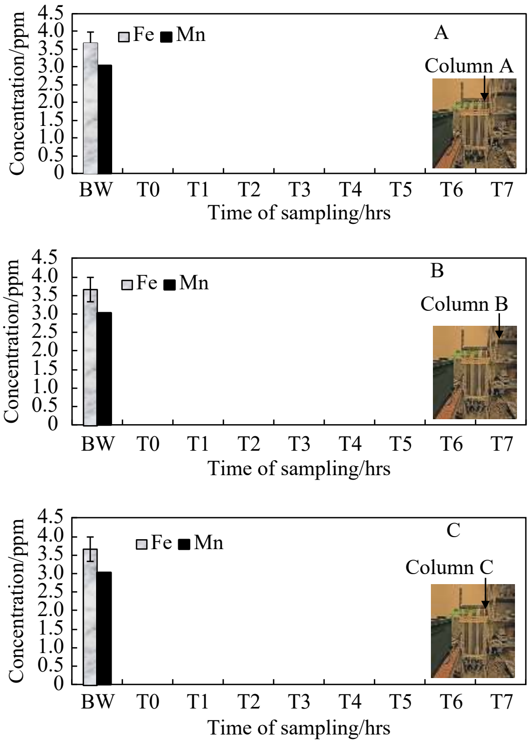

Fig. 8 Iron and manganese concentrations in the effluents collected at 90-minute interval (i.e. $\Delta T = T1-T0 = 90$ min) and in blank water (BW) in downward flow mode of groundwater

Fig. 9 Experimental site for testing filtering material to minimize iron induced clogging issue

7 Summary

Rapid depletion of water resources due to the increase in world's population and abrupt global climatic change demands the application of artificial recharge (surface and deep systems) to enhance the groundwater resources. However, the recharge well clogging has been a critical problem for the system to operate efficiently. Clogging can be generally categorized into physical, chemical and biological types, caused by complex interdependent mechanisms and it is fairly difficult to distinguish/uncouple them. On one hand, clogging increases the operational and maintenance cost resulting in the short life cycle of recharge systems. On the other hand, the recharge water quality requires special attention to minimize clogging. Fe and Mn oxidation under low O_2 concentrations play a vital role in chemical clogging mechanism. Although clogging caused by suspended particles present in the recharge water has been extensively investigated, studies regarding the clogging caused by suspended solids (finer particles) with their source from the aquifer have scarcely been documented and need further research. Most numerical and mathematical models predicting the movement of finer particles in the aquifer are quite site-specific, which requires more basic influencing factors to be included for their general validity. In order to estimate clogging due to the mobilization of particles, a critical hydraulic gradient or critical velocity (primarily based on diameter of soil particles) should be determined and characterized by considering the piping effect of earth fill dams. Mostly, special treatments are required for clogging prevention and redevelopment of the recharge systems with passage of time; therefore, special charts/models suggesting site specific threshold values should be consulted for recommendations/guidelines. Pretreatment of recharge water as a preventive measure, and recharge cycles (surface systems) and frequent back flushing (deep system) should be deployed to redevelop the recharge systems. Nevertheless, different sophisticated but expensive techniques are available for redevelopment of recharge systems; however, there is still a dire need to explore/redesign inexpensive and eco-friendly methods/techniques/strategies to minimize clogging, particularly, in resource limited countries.

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