Review: Saltwater intrusion in fractured crystalline bedrock

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Abstract

During the past few years, the number of regional and national assessments of groundwater quality in regard to saltwater intrusion in coastal aquifers has increased steadily. However, most of the international literature on saltwater intrusion is focused on coastal plains with aquifers in unconsolidated material. Case studies, modelling approaches and parameter studies dealing with saltwater intrusion in those systems are abundant. While the hydrogeology of fractured rock has been intensively studied with both modelling approaches and parameter studies—mainly in relation to deep-laying fractured crystalline bedrock as potential waste repositories—case studies on saltwater intrusion in shallow fractured rocks are still an exception. This review summarizes the actual knowledge on saltwater intrusion in fractured crystalline rock. In combination with short overviews of the processes of saltwater intrusion, flow in fractured systems and the genesis of these systems, the review highlights the importance of the fracture systems and its specific characteristics. Fracture properties are a direct consequence of the geological history as well as the current situation of the coastal area. A holistic assessment of water quality in coastal areas hosting fractured crystalline bedrock therefore requires the combination of different approaches in order to investigate the impact of saltwater intrusion through the fractured system.

Keywords Saltwater intrusion · Salt-water/fresh-water relations · Crystalline rocks · Fractured rocks · Coastal aquifers

Introduction

During the last two decades, the groundwater situation has worsened in coastal areas around the globe. Additional to (over)exploitation of the water resources in densely populated and economically stressed coastal areas, these areas are facing new challenges related to globalization such as global migration and world-market trading, as well as the current security situation rerouting tourist flows (Post and Werner 2017). Especially during summer seasons, increased water demand due to mass tourism and agricultural water consumption can lead to a modification of the natural seawater–freshwater interaction and eventually to saltwater intrusion (SWI) into the coastal aquifer (Custodio 2010). The increasing number of regional studies or national review papers on saltwater intrusion (e.g. Werner 2010; Barlow and Reichard 2010; Carreira et al. 2014; Shi and Jiao 2014; Manivannan and Elango 2019; Jasechko et al.

2020; Idowu and Lasisi 2020; Jeon et al. 2021) affords the conclusion that this is a globally emerging problem.

The complexity of SWI can be simplified by regarding different directions of the saltwater encroachment separately. The direction is highly correlated to the dominating processes caused by both natural and anthropogenic factors. Lateral and upward SWI is mainly triggered by changes of the systems' boundary conditions, which are not constant over time. Onshore, the freshwater recharge is subject to seasonal as well as long-term fluctuations (i.e. climatic variations causing changes in groundwater recharge). Anthropogenic activities in coastal regions increase the naturally existing threat of SWI into the aquifer system. Especially the risk of upward SWI increases due to the (over)exploitation of freshwater resources, referred to as upconing (Reilly and Goodman 1987). Downward SWI is caused by saltwater inflow from the surface due to temporary (e.g. storm floods) or permanent (e.g. estuaries, marsh flats) saltwater flooding (Barlow and Reichard 2010). Persistent changes of the boundary conditions, i.e. sea level rise, have lasting effects on these dynamics. For a wide range of settings, coastal regions are more vulnerable to SWI caused by groundwater (over)exploitation than to SWI as a consequence of predicted sea level rise (Ferguson and Gleeson 2012).

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The intrusion of saltwater is causing severe problems related to agricultural and domestic usage of coastal water resources. For example, already a freshwater–seawater mixture containing 1.3% marine saltwater exceeds the EU drinking water standard for chloride (250 mg/L; EU 2020), assuming an average chloride concentration of seawater (19,000 mg/L; Barlow 2003). The term SWI defines the saltwater encroachment in an aquifer and should clearly be differentiated from other processes resulting in salt-enriched water. A few sources of salinity worth mentioning are immobile water from earlier transgressions, anthropogenic pollution (e.g. industrial effluents, road de-icing salts and land use activities like irrigation) and natural dissolution of rock salt (e.g. Allen et al. 2002; Allen 2004; Barlow 2003; Barlow and Reichard 2010).

Avoiding permanent damage to the freshwater resources requires sustainable management practices that do not always exist for coastal aquifer systems (Post and Werner 2017). One example of a lack of sustainable management involves the coastal areas of Sweden. Groundwater problems in coastal regions are usually not associated with the relatively sparsely populated but freshwater-rich countries in Scandinavia; however, the combination of geology and the specific conditions of water usage create challenges even there. Approximately one third of the Swedish population lives in coastal areas (<5 km away from the coastline; Svanström 2012) where groundwater often occurs in fractured crystalline bedrock or in relatively small, shallow, and isolated Quaternary sedimentary formations. A large number of the approximately 450,000 private wells in Sweden are located in these coastal areas or on islands (Maxe 2007; Earon and Olofsson 2020). The wells create pressure on groundwater resources in summer months due to the low natural groundwater recharge and increased water demand as a consequence of tourism or seasonal increase of population. In densely populated areas, like the Stockholm Archipelago, reports on drilled wells already mention saltwater intrusion in fractured crystalline bedrock due to overexploitation in the early 1980s (Sund and Bergman 1981).

International research on SWI mainly focuses on aquifers in unconsolidated sediments, including most of the developed approaches to investigate and mitigate SWI. It might be a fact of missing relevance to global water supply that quantitative analyses as well as conceptual approaches are lacking for SWI in fractured rock (Barlow 2003; Werner et al. 2013) but reports from different coastal areas have been mentioning SWI in fractured rocks caused by natural (e.g. Carr 1969) as well as anthropogenic factors (e.g. Tremblay et al. 1973) for several decades. Compared to other types of consolidated rock, for example limestone (e.g. Fleury et al. 2007), comprehensive overviews of SWI in fractured crystalline bedrock are still missing. Potentially affected coastal areas consisting of plutonics and metamorphics are highlighted in Fig. 1, which is based on the global lithographic map GLiM (Hartmann and Moosdorf 2012).

Werner et al. (2013) point out that (well-documented) case studies are of prime importance for research related to SWI. This might be especially true for fractured crystalline bedrock where SWI is closely connected to the geometry and orientation of the fracture system (Caswell 1979). The global dimension of problems caused by SWI in fractured crystalline bedrock—accounting for approximately 22% of the world's coastal lithology (see the table in the Appendix)—is largely obscured. Therefore, the aim of this study is to collect and analyse the internationally available literature on SWI in fractured crystalline bedrock. The collection encompasses studies that evaluate the status of SWI in crystalline bedrock and summarizes tools as well as approaches for a holistic SWI investigation. In combination with a general overview of fractured rocks and SWI, the collected studies will be used to not only point out the current research status, but also the missing links regarding the comprehensive analysis of SWI in fractured crystalline bedrock aquifers.

This paper summarizes the most important and theoretical aspects and processes of SWI in general, with a focus on those most relevant in crystalline bedrock. There is focus on the genesis of fracture systems in crystalline host rocks defining the specific hydrogeological properties. The status of practical knowledge is then illustrated by presenting actual studies carried out in relation to SWI in crystalline bedrock, and insights from related research which can directly or indirectly be applied to questions about SWI in crystalline bedrock, are summarized.

Processes related to saltwater intrusion

First reports on natural SWI date back more than 150 years (cf. Back and Freeze 1983; Custodio 2010; Houben and Post 2017). The first general scientific descriptions of SWI were published at the end of the nineteenth century. Based on field observations, Drabbe and Badon-Ghijben (1888) and Herzberg (1901) derived the first quantitative relationship of the saltwater–freshwater interface location as a linear function of the water-table elevation in steady-state conditions. The resulting conceptual theorem, the Ghijben-Herzberg theorem, is named after two of the leading authors. The conceptual model of a sharp interface is still frequently applied, although it does not account for mixing along the interface and therefore simplifies the problem (e.g. Mehdiadeh et al. 2017; Siena and Riva 2018). Whereas a sharp interface approximation can be applied under certain conditions (cf. Bear 1979), measurements in different coastal zones indicate a great spatial extension of a mixing zone between fresh and saltwater (e.g. Xue et al. 1993; Barlow 2003). Therefore, the validity of a sharp interface applied on real case scenarios is already limited in unconsolidated material (e.g. Reilly and Goodman 1985; Pool and Carrera 2011; Llopis-Albert and Pulido-

Fig. 1 Global coastal lithographic map excluding Antarctica: Red line indicates plutonics and metamorphics, black line the other first-level lithological classes (based on Hartmann and Moosdorf 2012). A detailed map can be found in the [Appendix](#)

Velazquez 2014; Siena and Riva 2018). Nevertheless, the application of the sharp interface approximation for sustainable water-resources management is a conservative measure, since it overestimates the frontal extent of the SWI and underestimates critical pumping rates (Pool and Carrera 2011).

The mixing zone describes a salinity concentration gradient zone between saltwater and fresh water due to dispersion, i.e. hydrodynamic dispersion and molecular diffusion (e.g. Cooper 1959; Allen et al. 2002; Werner et al. 2013). Along the gradient where concentration and fluid density varies between the two end-members (Lu and Luo 2010), groundwater flow is not static but flows in a vertical convection cell (density driven) transporting deep saltwater into the mixing zone (Cooper 1959). Hydrodynamic dispersion describes the effect of heterogeneity in a flow velocity distribution and plays a significant role in the changes and development of the lateral extent of the mixing zone (Abarca et al. 2007; Lu and Werner 2013). Hydrodynamic dispersion depends on the properties of the flowing media and is nonuniform. According to Abarca et al. (2007), longitudinal and transverse dispersion control the extent of the mixing zone on a larger scale. In dynamic systems and systems with larger dispersion coefficients, the mixing zone is generally thicker (Lu and Luo 2010; Lu and Werner 2013).

Particularly heterogeneous aquifers and hence fractured aquifers show a high variation in the location and spatial extension of the mixing zone (Allen et al. 2002). Especially on a local scale, system heterogeneity can have a strong effect along preferential flow paths (Werner et al. 2013), which needs to be assessed on a regional scale, e.g. by effective parameters in groundwater flow models (Post 2005). However, the principles and processes influencing the spatial extent of mixing zones are complex and not fully understood (e.g. Reilly and Goodman 1985; Lu et al. 2009; Werner et al. 2013), ranging from transient boundary conditions (short- and long-term) over hydraulic properties of the coastal region to anthropogenic influences (e.g. Cooper 1959; Allen et al. 2002; Michael et al. 2005; Lu et al. 2009; Werner et al. 2013). Spatiotemporal changes in salinity directly affect the density, so that groundwater flow in coastal aquifers cannot be

considered without solute transport (e.g. Dentz et al. 2006; Post and Abarca 2010). In fractured systems, groundwater flow depends on the heterogeneity of the permeability distribution, which is normally unknown. Solute transport in fractured systems is poorly predictable due to the complexity and scale-dependency of several involved processes (e.g. hydrodynamic dispersion, diffusion, density driven flow). The physical processes of flow and transport in single fractures are known (Bodin et al. 2003a), which also explains the abundance of different numerical approaches on the scale of single fractures (e.g. Bodin et al. 2003b); however, studies on density effects on flow and solute transport are still scarce.

Hydraulic dispersion in a fracture consists of three different mechanisms (Bodin et al. 2003a): Taylor dispersion, roughness dispersion and dispersion as a consequence of aperture variations. The Taylor dispersion describes the parabolic cross-sectional velocity distribution between the fracture walls in laminar flow conditions (Taylor 1953). Taylor dispersion depends both on the properties of the fracture (i.e. the fracture aperture) and on the properties of the flowing media (i.e. diffusion coefficient and mean velocity; Zhou et al. 2007). Hydrodynamic dispersion needs to be considered at a local scale as well as on the scale of fracture systems, due to variation of fracture width (Bodin et al. 2003a). These variations along the flow path also favour channelized or preferential flow on both scales (Tsang and Neretnieks 1998). In general, preferential flow develops along flow paths with the lowest hydraulic resistance (Tsang and Tsang 1989), resulting in heterogeneous advection, as a consequence of the distribution of the flow velocity in the fracture system. Within fractured systems, the activation of flow paths is related to flow conditions (i.e. baseflow, high flow) and therefore short-term changes in boundary conditions (Gentry and Burbey 2004). Due to the low porosity of unweathered crystalline bedrock, neglecting matrix diffusion might be valid (e.g. Guihéneuf et al. 2017); however, shallow crystalline bedrock exposed to extensive weathering might have an increased porosity circumjacent to the fractures where matrix diffusion is significant (Ohlsson and Neretnieks 1995); more details on solute transport in single fractures are provided by Bodin et al. (2003a).

Characteristics of fractured (crystalline) bedrock

Starting with the conceptual description of flow and solute transport in fractured rock by Snow (1965), fractured rock formations received attention as potential groundwater resources and waste repositories. This resulted in an increasing number of case studies supported by numerical groundwater modelling to better understand the groundwater flow in (crystalline) fractured rocks. Nevertheless, the primary purpose and focus of these studies were safety assessments for (toxic or radioactive) waste repositories in deep-lying crystalline bedrock (e.g. MacQuarrie and Mayer 2005; Tsang et al. 2015). The other major group of publications focusses on the numerical description of processes and effects of idealised or generalised heterogeneity, including fractures, connected to SWI or submarine groundwater discharge (e.g. Kerrou and Renard 2010; Lu et al. 2013; Sebben et al. 2015; Etsias et al. 2021). In general, literature related to hydrogeological aspects of fractures is abundant (Berkowitz 2002); hence, the following paragraphs will focus on properties in the topmost approximately 300 m of coastal areas, representing the typical depth of groundwater wells, and processes directly related to SWI in fractured crystalline bedrock.

Fractures are defined as generic discontinuities in bedrock that occurred in response to stress. During geologic history, different periods of stress distributions formed different fracture types in different types of bedrock, and hence shaped the properties influencing water flow (i.e. permeability; e.g. Banks et al. 1996; Evans et al. 1997; Baghbanan and Jing 2008). These stress distributions can be divided into three main groups (Banks et al. 1996): (1) paleo-stress fields that initially are evolving water-bearing fracture systems; (2) current in situ stress fields reshaping the existing fracture systems and (3) anthropogenic stress fields, caused by, e.g. fracking or explosions, influencing natural flow fields on a local scale. Stress in subsurface rocks can be forced by regional (e.g. pressure of overlaying bedrock) and global (e.g. tectonic) activities influencing unique characteristics such as the orientation and geometry of fractures. In general, fractures can be divided into two different classes, namely joints and faults (Berkowitz 2002). The differentiation is related to the processes forming the discontinuity and the resulting properties. Faults are the result of large-scale tectonic events, and therefore, if originating from the same event, are similar in orientation, which reduces the interconnection (Berkowitz 2002). The significance of fault zones on the regional water flow depends on several factors, foremost the orientation of the fault towards the general groundwater flow direction. Several other factors and the general structure of fault zones and their influence on groundwater flow are detailed in Caine et al. (1996), Evans et al. (1997), Gudmundsson (2000), Bense et al. (2013) and Roques et al. (2014).

Joints result from regional processes and are in general well connected due to their coverage and manifold orientation (Berkowitz 2002). One example of a regional process is the isostatic uplift of Fennoscandia (e.g. Dehls et al. 2000; Eronen 2005), which is expected to influence the differences of rock fracturing on a regional scale (e.g. Rohr-Torp 1994). Other in situ stresses on a regional scale are, for example, topographic anomalies, geological discontinuities, erosion or fluid pressure (Banks et al. 1996; Berkowitz 2002). In case the in situ stress equals or exceeds the mechanical strength of the bedrock, new fractures develop along the principle stresses of the stress field (e.g. Henriksen and Braathen 2006). In the shallow part of the bedrock, anisotropic stress fields result in a large range of fracture width (Banks et al. 1996). The abundance of fractures in the host rock decreases with depth up to 100–300 m below surface (Rutqvist 2015), due to prevailing isotropic stress in deep-lying bedrock (Acworth 1987). However, the actual state and evolution of the stress field has a large impact on the fracture closure, and therefore the hydrogeological properties of the single fracture as well as the hydraulics of the fracture system (e.g. Sayers 1990; Banks et al. 1996; Baghbanan and Jing 2008).

Stress fields, for example introduced by topographic anomalies, have a direct relationship to rock weathering (St. Clair et al. 2015). With an increasing number of open fractures, the vulnerability of the bedrock to weathering also increases (Acworth 1987). Consequently, different types of weathering, depending on site-specific characteristics such as rock types, depth to surface or climatic conditions, can alter the properties of the fractured system. St. Clair et al. (2015) provide an overview, including references, of these processes potentially developing new fractures or reactivated existing ones. In general, weathering results in disaggregation of the topmost part of the crystalline bedrock (saprolite) and the fracturing of the first several meters of the bedrock (saprock). Therefore, stress fields are an important boundary condition for groundwater flow and weathering in fractured crystalline bedrock (St. Clair et al. 2015), even though the interconnection between stress and hydraulic properties is site-specific (e.g. Baghbanan and Jing 2008). In a simplified way, the effect can be described as positive feedback of groundwater flow in opened and connected fractures and chemical weathering processes to regional stress fields, called self-organization (Ortoleva et al. 1987). As an additional consequence of chemical weathering of certain minerals, open fractures can be clogged—for example due to the abundance of clay minerals in the hosting rock (e.g. Wright 1992).

The specific profile of weathering (Fig. 2) depends on the site-specific characteristics including the properties of the bedrock, climatic conditions, and formation history. The landforms created by in situ weathering are as manifold as the site-specific characteristics ranging from profiles with sparsely localized disaggregated bedrock in glaciated regions

Fig. 2 Examples of the specific profile of weathering in **a** glaciated regions and **b** (sub)tropical regions

(Fredin et al. 2017), to deeply weathered basement rocks in tropical and subtropical regions (Wright 1992). Especially the weathering interface depth between saprolite and saprock (Fig. 2) has a direct influence on processes related to groundwater recharge and preferential horizontal groundwater flow (Nicolas et al. 2019). According to Lachassagne et al. (2001), the combination of a thick saprolite, a saprock with open vertical fractures and well-developed fractures in the basement rock creates a favourable system for enhanced groundwater flow, which on the other hand might also be prone to SWI. It can be concluded that a conclusive analysis of SWI in fractured crystalline bedrock needs to consider both the geological history and current in situ stress field (Larsson 1972; Sund and Bergman 1981).

The result of the impact on the crystalline bedrock over a geological timescale is a complex system with hydrogeological heterogeneity on different scales. Based on an analysis of 13,600 drilled wells from Sweden and Norway, Henriksen (2003) point out that there is no clear regional correlation of hydraulic conductivity and several local properties such as isostatic uplift rate, rock type, soil type, topography, or recharge; and he concludes additionally that no combination of these parameters is significant enough to explain the local variations in well yield. In general, the permeability of fractured crystalline bedrock ranges over several orders of magnitude (e.g. Rutqvist 2015; Worthington et al. 2016) and therefore can differ more within one bedrock type than between different bedrock types (Banks et al. 1996); this despite the fact that fissure patterns differ greatly depending on the rock type (e.g. Sund and Bergman 1981; Acworth 1987). However, the permeability of fractured crystalline rock is highly dominated by the conductance of single features and their density, length, and connectivity (Singhal and Gupta 2010). Flow occurs mainly in a small number of fractures (first and second order), depending on the host rock ranging from over 90% in granite to roughly 65% in

basalt (Worthington et al. 2016). In contrast, unweathered crystalline bedrock has very low porosity and permeability (Acworth 1987); however, for this condition, hydraulic properties are barely reviewed and unknown (Hjerne and Nordqvist 2014). One exception is the rough correlation between hydraulic conductivity and porosity based on a large data analysis from different rock types by Guimerà and Carrera (2000).

Case studies in fractured crystalline bedrock with special focus on SWI

Werner et al. (2013) point out that fieldwork is a crucial factor in understanding the impact of aquifer heterogeneity on SWI; however, case studies on SWI in fractured crystalline bedrocks are scarce, with the exception being coastal areas dominated by basalt bedrock. Due to the high permeability of these volcanic rock aquifers, the properties are more similar to sedimentary bedrock (i.e. limestone and sandstone). Overviews on case studies and general conception that focused on groundwater circulation in young basaltic bedrock can be found in Hildenbrand et al. (2005) or Singhal and Gupta (2010). The main focus of the present article is on intrusive igneous and metamorphic rocks. Due to the low number of case studies available in international literature, the following overview also takes studies into account that deal with general regional flow patterns in fractured crystalline coastal bedrock and studies where SWI is only a side-aspect. Table 1 shows an overview of peer-reviewed articles related to SWI in fractured crystalline bedrock and links to Table 2, which lists different investigative techniques and methods used, or of potential use in coastal crystalline bedrock.

Most of the case studies related to SWI in fractured crystalline bedrock, except from Mätkki (2003) and Aretouyap et al. (2020), apply at least one analysis tool based on

Table 1 Case studies focused on saltwater intrusion (SWI) or more broadly on groundwater (GW) in coastal fractured crystalline rock. Note: Some of the studies focus on other geological units but also consider fractured crystalline rocks

Reference	No. of sample points (e.g. wells, cross-sections)	Country	Fractured crystalline rock type according to the publication	Problem/reason for the investigation	Type of investigation (see Table 2)	Main result	General, transferable results
Sund and Bergman (1981)	13	Sweden	Gneiss	SWI risk assessment	1+2	Overexploitation leads to SWI in drilled wells	–
Karro (1999)	4	Finland	Granite, gneiss	Regional GW pollution assessment in glacial deposits	1	SWI does not play a significant role in the changes of water quality but relict seawater does	–
Mälikki (2003)	0	Finland	Gneiss, migmatites, granites	Groundwater flow conditions in the coastal bedrock area	2	Regional estimation of the GW discharge from coastal bedrock	–
Karro et al. (2004)	7	Estonia	Granite	Hydrogeological characterization of SWI	1	Saline water from the crystalline bedrock is the main source of salinity in the unconsolidated aquifer	–
Subba Rao et al. (2005)	20	India	Gneiss + different intrusions	Regional GW pollution assessment	1	SWI is one of the reasons for groundwater contamination	–
Jayasena et al. (2008)	90	Sri Lanka	Gneiss + granite intrusions	Regional GW pollution assessment	1	Relative abundance of cations relates strongly to local lithology	–
Park et al. (2012)	2	South Korea	Granite/gneiss	Hydrogeological characterization of SWI	1+2	Extent of SWI depends on (hydrogeological) properties of fractures	Persistent extraction of GW intensifies SWI in tidally forced, coastal fractured aquifers
Lim et al. (2013)	47	South Korea	Volcanic rocks/granite	SWI around oil storage caverns	1+4	Hydrogeological heterogeneity of both the fracture system and the cavern facilities result in spatial variations in hydrochemistry	–
Singaraja et al. (2014)	100	India	Gneiss, charnockite, granite, quartzite	Hydrogeochemical processes in coastal groundwater	1+4	SWI is the main factor controlling groundwater chemistry	–
Singaraja et al. (2015)	135	India	Gneiss, charnockite, granite, quartzite	Regional GW pollution assessment	1+4	SWI is the main factor controlling groundwater chemistry	–
Les Landes et al. (2015)	>1,000	France	Crystalline basement (gneiss, granite, basalt)	Residence time of saline fluids in continental crystalline rock aquifers	1	Salinity distribution is in good agreement with limits of historical transgressions	Constrains on SW circulation in hard rock aquifers on a large scale
Iwatsuki et al. (2015)	8	Japan	Basement granites	Hydrochemical changes during construction and operation of an underground facility in deep crystalline rock	1+4	Upcoming as main driver of hydrochemical changes is dependent on the distance to the facility	–

Table 1 (continued)

Reference	No. of sample points (e.g. wells, cross-sections)	Country	Fractured crystalline rock type according to the publication	Problem/reason for the investigation	Type of investigation (see Table 2)	Main result	General, transferable results
Walter et al. (2017)	321	Canada	Gneiss	Groundwater quality and the evaluation of the impact of different salinization paths	1 + 4	Water–rock interaction is primary reason for increase of salinity in crystalline bedrock	Definition of water–clay interaction as an additional source of salinity in sedimentary deposits
Stumm and Commo (2017)	3	USA	Crystalline basement	Delineation of SWI in a sedimentary aquifer overlaying crystalline bedrock	3	–	–
Kanagaraj et al. (2018)	33	India	Charnockite	Hydrogeochemical processes in coastal groundwater	1 + 4	SWI is one factor increasing the groundwater salinity	–
Arétouyap et al. (2020)	50	Cameroon	Gneiss	Interpretation of lineament effects on SWI	5	Perpendicular lineament orientations might foster SWI	–

groundwater samples taken from different wells in coastal areas. The most common method applied is the analysis of major ions measured in the groundwater samples. Presented in either Piper diagrams (Piper 1944) or in different kinds of mass ratios (e.g. chloride/bromide), major ions are used to evaluate the water quality on a regional scale. At a point scale, Sund and Bergman (1981), Park et al. (2012), Les Landes et al. (2015) and Stumm and Como (2017) take chloride (Cl^-) or electrical conductivity (EC) measurements or bore-hole logs along one or different wells. Stumm and Como (2017) combine the chloride measurements with borehole logs of focused electromagnetic induction but do not discuss the results in the deeper bedrock parts of the observed wells. Walter et al. (2017) extend the hydrogeochemical analysis by measuring minor and trace elements for a large dataset of over 300 water samples. The data set is the second largest of the case studies, only excelled by the enormous number (over 1,000 samples) considered by Les Landes et al. (2015). It must be noted that both studies do not exclusively include samples taken from fractured crystalline bedrock. This also influences the numbers of sampling points given in Table 1, which does not always represent the real numbers of sampling points related to fractured crystalline bedrock. The remaining studies base their regional analysis on two (Park et al. 2012) up to 135 (Singaraja et al. 2015) sample sites. These numbers should not be taken as quality measures since the variety of research aims and approaches between the case studies is vast (cf. Table 1). To extend the hydrogeochemical analysis, Lim et al. (2013) and Kanagaraj et al. (2018) sample stable isotopes additional to major ions to analyse the origin of the water in the coastal zone, and hence also the origin of salinity.

The majority of studies identify SWI as the main process that increases the groundwater salinity in the coastal area. Other processes worth mentioning here are mixing with relict seawater (Karro 1999; Karro et al. 2004; Les Landes et al. 2015) and water–rock interactions (Jayasena et al. 2008; Walter et al. 2017). In all cases, SWI is caused by groundwater extraction in the coastal area. Only Park et al. (2012) mention tidal influences as an additional process which is however intensified by groundwater pumping.

All studies listed in Table 1 focus on a larger scale and none on a single fracture or a fracture network with defined boundaries. In general, it can be noted that the description of fracture properties is, if at all, only a side aspect. Most studies give a general overview of the regional geology, and in exceptional cases, sometimes with hydrogeological properties of different units, e.g. hydraulic conductivity (Lim et al. 2013). Descriptions of the single fractures or fracture networks are generally incomplete and lacking basic properties, for example the orientation of the fractures. This also includes the lack of standard (structural) geology tools such as rose diagrams to indicate the general orientation(s) of fractures or stereographic projections. The most detailed description of the fractured

Table 2 Summary of the methods used (based on Table 1) or of potential use for the study of SWI in crystalline bedrock

ID	Field of research	Attribute under investigation	Method/techniques
1	Hydrogeochemical characterisation	<ul style="list-style-type: none"> • Isotopes • Major ions • Physicochemical parameters • Trace elements 	<ul style="list-style-type: none"> • Chloride distribution (spatial/vertical) • EC distribution (spatial/vertical) • Graphical interpretation (e.g. molar ratio, Piper/Chadda plots, sodium adsorption ratio)
2	(Hydro)geological characterisation	<ul style="list-style-type: none"> • Lineaments • Hydrogeological parameter • In situ stress^a • Host rock/minerals^a 	<ul style="list-style-type: none"> • Orientation (e.g. rose diagram) • Lineament density • Fracture distribution map • Borehole imaging • Pumping test analysis • Hydraulic splitting^a • Thin section analysis^a • Isotope analysis^a • Fluid inclusion analysis^a • Trace element analysis^a • Redox front analysis^a
3	Geophysics	<ul style="list-style-type: none"> • Stratigraphy • Rock texture and structure • Lithology 	<ul style="list-style-type: none"> • Vertical electrical sounding (VES) • Electromagnetic-induction Logging (EM) • Flowing fluid electrical conductivity (FFEC)^a • Proton magnetic resonance (PMR)^a • Nuclear magnetic resonance (NMR)^a • Electrical resistivity tomography (ERT)^a
4	Statistics and data analysis	<ul style="list-style-type: none"> • Parameters listed in 1 and 2 	<ul style="list-style-type: none"> • Principal component analysis (PCA) • Hierarchical cluster analysis (HCA) • Correlation analysis • Factor analysis • Tidal oscillation analysis
5	Remote sensing	<ul style="list-style-type: none"> • Earth surface 	<ul style="list-style-type: none"> • Satellite/aerial photographs • LiDAR

^a Methods of potential use for the study of SWI in crystalline bedrock

network is given by Mätkki (2003), who describes major and minor faults as well as fractures in orientation and inclination as well as permeability. Iwatsuki et al. (2015) present all information related to the fracture network in a cross-section of the area under investigation. Aretouyap et al. (2020) combined remote sensing and other different geological data to define the length and orientation of lineaments in order to make a preliminary delineation of SWI in fractured crystalline rock. Less detailed descriptions of the fracture systems can be found in Sund and Bergman (1981), Subba Rao (2005), Les Landes et al. (2015) and Walter et al. (2017), studies which all consider major faults in their assessments. Information regarding inclination of the faults are mostly missing with a few exceptions namely in Mätkki (2003), Iwatsuki et al. (2015) and Walter et al. (2017). Park et al. (2012) apply an acoustic televiewer in the two boreholes used in the field study to map the fractures around the boreholes. Based on this analysis, the authors conclude that the changes in the mixing zone extent are related to the location of conductive fractures. The weathering interface between saprolite and saprock is addressed in seven studies, whereby Karro et al. 2004, Subba Rao (2005), Jayasena et al. (2008), Les Landes et al. (2015) and Iwatsuki et al. (2015) quote former studies for the general depth of the interface, while Park et al. (2012) guessed the

depth of the interface based on the casing of the bore wells. Furthermore, Kanagaraj et al. (2018) applies a geophysical approach (vertical electrical sounding) for the identification of the interface depth.

A few case studies apply additional approaches in order to define the spatial extent of SWI in fractured crystalline bedrock. The analysis of Park et al. (2012) is based on extensive analysis of a different kind of time series (e.g. drawdown curve, tidal oscillation). They also include classical borehole analysis such as pumping test analysis to obtain hydraulic conductivity in the vicinity of the bore wells. Additionally, Park et al. (2012) use high-frequency EC measurements, which they connect to tidal level measurement in the study region. Karro (1999), Singaraja et al. (2014) and Singaraja et al. (2015) make use of standard statistics (i.e. correlation analysis) adopted regarding major ion concentrations. In all cases, these methods are used as an additional tool, rather than a stand-alone approach, to analyse potential sources of contamination. Two of the studies also include a time perspective in the statistical analysis by analysing samples from different seasons or years (Karro 1999; Singaraja et al. 2014). Lim et al. (2013) and Walter et al. (2017) take the analysis one step further and apply advanced statistical tools to the ion measurements. Whereas Lim et al. (2013) used principle

Fig. 3 Detailed map of the world coastal lithography (excluding Antarctica) based on the global lithological map GLiM (Hartmann and Mossdorf 2012)

component analysis (PCA) to identify different contamination sources, Walter et al. (2017) complete their analysis with a hierarchical cluster analysis (HCA); they link each of the clusters to a different kind of host rock and different processes altering the “background” concentration, thereby pointing out two different salinization sources.

The literature review reveals the variety of topics and applied approaches in the study of SWI in fractured crystalline bedrock; however, analyses of SWI in fractured crystalline bedrock are mostly connected to water management issues rather than fundamental research. Therefore, hydrogeochemical analysis is the most frequently applied analysis tool. To the knowledge of the authors, no fundamental research exists specifically focusing on the processes involved in SWI in fractured rock. Different to other groundwater flow processes, for example in deep crystalline bedrock, no specific field sites exist to study SWI. As mentioned by some of the studies, even water sampling can be a serious problem due to unavailability of observation wells, i.e. not used for groundwater pumping (e.g. Park et al. 2012; Walter et al. 2017). The poor data coverage in terms of geology and technical specification of the well (e.g. drilling depth and casing depth) adds to the problem (Walter et al. 2017). These circumstances complicate the interpretation of the results even further. The other major obstacle in the studies is the lack of information on the complexity of the highly conductive structures and the bedrock (e.g. Mäkki 2003; Les Landes et al. 2015), including the main hydraulic properties, the distribution in different areas, and the potential mechanisms influencing the chemical composition as well as the local and region flow system. To complete the hydrogeochemical interpretation of the results rather than to overcome this specific problem, Walter et al. (2017) suggest incorporating the chemical analysis of the host rock. Classical geological approaches such as thin section

analysis, could help to define the specific composition of the host rock in the study region. Similar to the mineral composition of the rock, former processes influencing the chemical composition of the water (e.g. immobile water from earlier deposition) need to be accounted for (Les Landes et al. 2015).

Insight from related fields of research

The literature on both SWI in general and groundwater flow in crystalline bedrock is abundant. At the same time, studies directly focused on SWI in crystalline bedrock are still scarce as can be seen from the last section (on case studies). The studies identified through the literature review presented in Table 1 cover most of the coastal areas where crystalline bedrock is the dominating lithology (Fig. 1). Most of the field studies base their assessment of SWI on physicochemical characterization of water samples taken from wells, mainly used for water supply, i.e., pumped wells; however, boreholes run the risk of providing hydraulic shortcuts and therefore give a blended signal from different depths (Pool and Carrera 2011). The risk might be even more pronounced in fractured systems where wells can intersect highly conductive structures with different orientations and depths (e.g. Caswell 1979). Especially wells drilled for the purpose of local or larger-scale freshwater supply might tap different highly conductive features in order to maximize the well yield. The limited validity of borehole data on a larger scale is an additional disadvantage of analysis solely based on borehole data since SWI needs to be considered as a process of three dimensions (Abarca et al. 2007).

The risk of SWI in fractured crystalline bedrock is determined by historical and current stress fields as well as hydrogeochemical changes (i.e. dissolution, precipitation and remineralisation) within the fractures influencing local flow

permeability (Tsang et al. 2015). Therefore, assessment of SWI in fractured crystalline bedrock needs to combine different methods accounting for the aforementioned processes. Allen et al. (2002) give a good example of addressing the problem of SWI in fractured sedimentary rocks on a larger scale, whereby they applied an integrated geophysical, geological and geochemical approach to investigate the potential SWI for a sedimentary bedrock aquifer in Western Canada. Recently, Banks et al. (2021) published a similar study investigating groundwater lens dynamics of a sedimentary bedrock island. To improve the knowledge on SWI in crystalline bedrock, it may thus be a valid approach to try and combine additional methods applicable for the study of SWI in fractured crystalline bedrock. This section indicates additional methods, which will be briefly presented. All methods applied in the studies of section ‘Case studies in fractured crystalline bedrock with special focus on SWI’ and the additional methods presented here, are summarized in Table 2.

Geological approaches

The importance of the geological history has been highlighted in several sections of this review. On a larger scale, or in remote areas, the application of remote sensing technologies to map geological and geomorphological features might be a first step in understanding the geological history of the area (e.g. Mabee et al. 1994; Henriksen and Braathen 2006; Vasuki et al. 2014; Schreiber et al. 2015). Independent of the approaches used to extract lineament information and analyse lineament properties, e.g. the fracture orientation by using rose diagrams, any remote sensing study needs to be validated by ground truthing (e.g. Schreiber et al. 2015). Further information on the topic can be found, for example, in the previously mentioned studies or in Sander (2007); however, due to the diversified history of crystalline bedrock, an investigation of the surface might not be sufficient to characterize the properties of fractures. Outcropping fractures most likely change their properties with depth due to the discussed processes of weathering, increasing stress and remineralization (Mabee et al. 1994), which once again shows the necessity of local or regional investigations.

Especially, regarding Nordic countries, investigations exist on the impact of geological history on groundwater flow or well productivity (e.g. Larsson 1972), due to the fact that groundwater in fractured crystalline bedrock not only plays an important part in water resources management (e.g. Earon and Olofsson 2020), but also in infrastructural aspects (e.g. Kitterød 2015). Several of these reports mention that current stress fields (e.g. due to isostatic uplift) overprint the fractured systems created by old tectonic stress fields (e.g. Rohr-Torp 1994; Gudmundsson et al. 2002). Current *in situ* stress can be determined by hydraulic splitting of the host rock, for example in borewells (Henriksen and Braathen 2006). This information

combined with other geological information can be used as input variables for numerical models simulating the fracture growth (e.g. Gudmundsson et al. 2002). In combination with groundwater flow and hydrogeochemical models, these models could be used to describe the genesis of the fractured system and therefore define the hydrogeological properties of a system, an approach frequently used in karst hydrogeology (e.g. Gabrovšek and Dreybrodt 2001). Another method to determine the groundwater flow in fractured rocks is the injection of dye tracer, for example during drilling of a new well (e.g. Gustafsson and Andersson 1991). This approach can be combined with several other techniques, for example radar tomography (Day-Lewis et al. 2003), but are only valid on a small scale, i.e. along the flow paths.

Geophysical approaches

Several studies have proven the applicability of geophysical techniques in investigating SWI. In general, geophysical techniques are applied to locate the interface between freshwater and saltwater or to characterize aquifer heterogeneity both in unconsolidated (e.g. Lang et al. 2004; Luján and Romo 2010) and sedimentary bedrock (e.g. Allen et al. 2002; Comte et al. 2017). Due to the specific properties of fractured crystalline bedrock, the selection of possible methods is not as broad as for sedimentary aquifers. In general, the methods can be divided into two different types of approaches—the first one focuses on borehole logs and the description of the vicinity of the well, and the second one defines the properties on a larger scale. One method used to define certain properties from a borehole log is presented in Table 1. Stumm and Como (2017) apply electromagnetic-induction logging (EM) to estimate the chloride concentration, mainly in the glacial aquifer. With a high number of borehole logs, hydrological information can be achieved on a regional scale—for example, the thickness of saprolite and saprock as well as the depth of the weathering interface (e.g. Raji and Abdulkadir 2020). Several other techniques are available for the investigation and description of highly conductive structures along a bore well—for example flowing fluid electrical conductivity (FFEC; Tsang et al. 1990, 2016) to mention only one. Comprehensive overviews on the topic can be found in Keys (1996) or Spies (1996). In the absence of wells or to gain information on a large scale, other techniques to investigate groundwater storage in bedrock can be used; one example is the study of Kanagaraj et al. (2018) who used vertical electrical sounding (VES). Other examples for this method can be found for example in Maiti et al. (2012 and 2013). Similar to the methods applied in boreholes, these techniques—e.g. electrical resistivity tomography (ERT), proton magnetic resonance (PMR), nuclear magnetic resonance (NMR)—are able to define the characteristics of saprolite, saprock and the interface between

them (e.g. Griffiths and Barker 1993; Wyns et al. 2004). Some of these methods can be used in airborne specifications to map lineaments as well as to characterize the fractured bedrock properties in terms of hydrogeological characteristics (Chandra et al. 2019). Several other methods exist in the characterization of groundwater flow and storage and the general characterization of the bedrock (cf. Singhal and Gupta 2010); thus, this short summary should not be taken as an exhaustive overview.

Geochemistry approaches

The physicochemical properties of groundwater are the result of a combination of different processes depending on the system as well as a time component. In fractured crystalline bedrock, the properties are dominated by the rock type as well as potential fracture fillings. SWI or other sources of contamination (natural as well as anthropogenic) create multiple mixing combination on a regional scale. Therefore, most studies have a local acquisition with limited potential to be generalized. In general, geochemical analyses in fractured crystalline bedrock have to take two different time frames into account—a short one following the active flow path of the water from the recharge area to the coastal area, and a longer one of mostly stagnant flow paths. Several of the case studies point out that stagnant water, e.g. originated from previous transgressions, interferes with the active part of the flow system. Walter et al. (2017) present one of the studies analysing different flow paths from the origin to the sampled wells. Another study, including the flow path in crystalline fractured rock but focusing on groundwater in a coastal plain, is presented by Shi et al. (2018). In addition to the interaction with the bedrock, the authors also include different anthropogenic sources of contamination in their assessment. A similar kind of process description based on stable isotopes for deep-laying crystalline bedrock is presented by Kloppmann et al. (2002). The overview summarizes different processes in different parts of the world, altering the isotope compensation of saline water. Another approach to assess the regional history and therefore the characteristic properties of the crystalline bedrock based on geochemical measurements of the host rock is the so-called paleohydrogeology (e.g. Tullborg et al. 2008; Drake and Tullborg 2009). These methods combine several analyses of the minerals, for example the isotopic composition, fluid inclusion and thin section analysis.

Conclusions

The presented review of SWI in fractured crystalline bedrock reveals that the topic is generally addressed from very different angles. Most of the case studies that were identified through the review concern the water quality in coastal areas,

where SWI is identified as the only or one of several potential contamination sources. The low number of studies carried out may indicate that this problem only is of local or, in general, of minor importance. Taking the abundance of crystalline bedrock in coastal areas and the magnitude of the globally emerging SWI problem into account, this seems to be unlikely. Thus, another explanation could be that studying SWI in fractured crystalline bedrock in a scientifically sound and publishable manner, requires a lot of effort as well as sophisticated methods, due to the complexity and heterogeneity of the hydrogeological setting. Investigating the current and future risk of SWI in fractured crystalline bedrock requires expertise and approaches from different research fields of geology, hydrogeology, hydrochemistry, geophysics and even others not mentioned here.

In particular, the characterization of the highly complex fractured system, including hydrodynamic characteristics, flow paths and possible entry points, requires a large investigative effort, which is not always feasible. This might be the reason that system complexity is frequently mentioned in the studies, but in most case studies not sufficiently addressed. The complexity of natural fracture systems might also explain the divergence between the number of case studies and numerical modelling approaches, where certain simplifications (most often in regards to the fracture system) are used to define the problem.

The holistic assessment of SWI in fractured crystalline bedrock needs to consider different kinds of processes on different timescales. The geological timescale is important to describe the system's specific characteristics as well as initial conditions (e.g. spatial distribution of salinity) for short-term processes with varying boundary conditions (i.e. sea level changes and recharge). Some of the short-term processes involved may be highly dynamic and evaluation of longer time series are required to capture their influence. The specific hydrogeological properties, which are a direct result of the history of the coastal area, and the wide variety of research questions that form the background of the respective study, lead to the broad variety of the applied approaches within the relatively few studies that could be identified. Therefore, a standard approach for investigating SWI that could be applied in a wide range of crystalline bedrock settings cannot be identified from the literature, making it difficult to compare or transfer results from one study to another.

The review highlights that SWI in fractured crystalline bedrock is or potentially could be a problem on almost all continents. In certain regions, for example the Nordic countries, the magnitude of the problem increases. Based on the coastal lithology, 22% of the world's coastline consists of either plutonic or metamorphic rock potentially hosting fracture systems, which justifies any effort to gain more data and hence a better understanding of the processes involved in SWI in fractured crystalline bedrock.

Appendix

Table 3 Percentage of coastal lithography per continent. Lithography according to the first level lithological class of the Global Lithological Map (GLiM; Hartmann and Mossdorf 2012)

Region	Siliciclastic sediments			Carbonate-rich sedimentary rocks and evaporites			Volcanics			Plutonics			Meta-morphics	Other units		
	su	ss	py	sc	sm	ev	va	vi	vb	pa	pi	pb		wb	ig	nd
N. America	8	15	1	8	30	0	1	2	4	5	1	1	18	1	6	0
S. America	24	24	1	3	10	0	1	1	3	12	2	1	14	1	0	0
Europe	14	13	0	16	19	0	1	1	5	9	0	1	18	0	2	0
Africa	33	20	0	13	5	0	0	0	4	2	0	0	22	0	0	0
Asia	26	18	1	5	20	0	1	6	4	8	0	1	7	0	1	0
Australia	44	12	1	11	12	0	1	2	4	3	1	2	5	1	0	0
World	20	17	1	9	21	0	1	3	4	7	1	1	13	0	3	0

su unconsolidated sediments; *ss* siliciclastic sedimentary rocks; *py* pyroclastics; *sc* carbonate sedimentary rocks; *sm* mixed sedimentary rocks; *ev* evaporites; *va* acid volcanic rocks; *vi* intermediate volcanic rocks; *vb* basic volcanic rocks; *pa* acid plutonic rocks; *pi* intermediate plutonic rocks; *pb* basic plutonic rocks; *mt* metamorphics; *wb* water bodies; *ig* ice and glaciers; *nd* no data

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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