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Quantitative Assessment of the Environmental risks of Geothermal Energy：A Review

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Abstract

Over recent decades, the use of geothermal energy for heating supply and power generation has increased significantly in the world, owing to its low carbon emissions. However, a series of emerging negative environmental impacts of geothermal energy development and operation have been drawing increasing attention from the government and the public. In this context, the present study provides an overview of the quantitative assessment of the environmental risks of geothermal energy from seismic hazards, human health, ecology, and economy respectively. The constraints on constructing assessment frameworks are also discussed. Furthermore, a preliminary concept for an integrated framework is proposed to assess environmental risks of geothermal energy comprehensively from multiple perspectives. To enhance the accuracy and reliability of the proposed framework, a data-sharing platform needs to be built to develop multi-disciplinary modeling further.

Keywords: Geothermal energy; Environmental risks; Quantitative assessment; Review

1. Introduction

As a form of clean energy with abundant reserves, geothermal energy has contributed to an increasing share of the global demand for energy and greenhouse gas (GHG) mitigation (Hulen et al., 2001). The total thermal energy contained in the Earth is roughly 12.6 x 10^{12} EJ, of which about 5.4 x 10^{9} EJ occurs in the upper 50 km of the crust (Dickson and Fanelli, 2003). Using the 2018 global energy consumption of approximately 580 EJ/yr as a base, the geothermal reserves within a depth of 50 km could notionally meet the world's energy needs for 9.3 million years or so (Hou et al., 2018; BP, 2019). More realistically, the technically feasibly geothermal potential is estimated to lie between 118 EJ/yr at a depth of up to 3 km and 1,109 EJ/yr to 10 km depth (Rowley, 1982; Stefansson, 2005).

Geothermal energy is of great importance for reducing people's reliance on fossil fuel, widely available for power generation, buildings heating, domestic water heating, and potentially hydrogen production (Ahmadi et al., 2018; Chahartaghi et al., 2019; Ghazvini et al., 2019). The application of geothermal energy for power generation and heating supply have been increasing steadily (Bertani, 2015; Lund and Boyd, 2015). According to the BP Statistical Review of World Energy 2019, geothermal power capacity grew by 568 MW up to 14.6 GW at an annual rate of 4.0% in 2018, with over half of the incremental capacity contributed by Turkey and Indonesia. By the end of 2018, the top three countries for cumulative installed geothermal power capacity were the US, Indonesia, and the Philippines (Fig. 1). In contrast, China is the biggest consumer of geothermal energy for direct use, accounting for almost three-quarters of the world total, followed by Turkey, the US, and New Zealand (Fig. 2) (IEA, 2018).

The rapid development of geothermal energy has been accompanied by an increasing realization by the public of its negative impacts on the local environment. For example, geothermal steam contains non-condensable gases (NCG, which cannot be liquefied) such as carbon dioxide and hydrogen sulfide, and may also carry traces of mercury, arsenic, and radon (Barbier, 2002; Sharifi et al., 2016). Additionally, an increasing number of geothermal wells pose significant threats to groundwater quality and drinking water production (Bonte et al., 2011). These potential environmental impacts may have far-reaching consequences for the local human health, ecology, and economy, which, in turn, may affect social acceptability and investors' decision-making (Pellizzone et al., 2015; Meller et al., 2018). Certainly, in addition to environmental risks, geothermal systems are also facing other risks that are not discussed in this study but important. For example, risks of shallow geothermal systems include the decline in borehole productivity and injectivity (Banks and Birks, 2020).

The substantial literature addressing the evaluation and assessment of geothermal energy, mostly focuses on direct costs such as exploration, construction and operation costs, but commonly ignores indirect costs such as the external environmental costs (Abraham, 2006; Daniilidis et al., 2017; Zhang et al., 2019). Other parts of the literature highlight positive contributions of geothermal energy development to carbon emissions reduction, or consider carbon emissions as the only benchmark to assess environmental impacts of geothermal energy (Atkins et al., 2010; Martínez-Gomez et al., 2017; Al Irsyad et al., 2019). Such studies neglect negative effects arising from geothermal energy development, such as induced seismicity, and may result in the value of geothermal projects being overestimated. In this context, the current study aims to fill this gap in the literature.

The present paper examines the environmental risks of geothermal energy development and its quantitative assessment methodologies holistically. Section 2 summarizes the negative impacts of geothermal energy development on the environment from the standpoint of spatial distribution. Section 3 introduces existing methods to evaluate these risks caused by geothermal energy development and their ramifications from the perspectives of geological hazards, human health, ecological systems, and the economy. Section 4 discusses the constraints faced in assessing these indirect costs and provides a preliminary framework for evaluating the environmental risks of geothermal energy development.

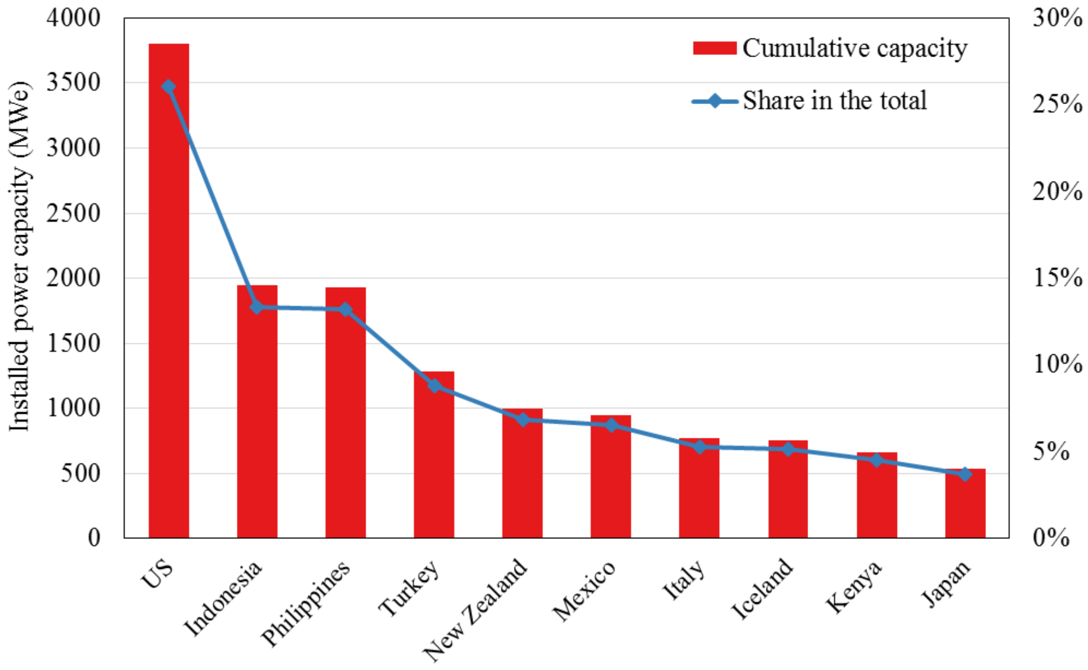


Fig. 1 Cumulative geothermal power capacity in main utilizing countries (2018)

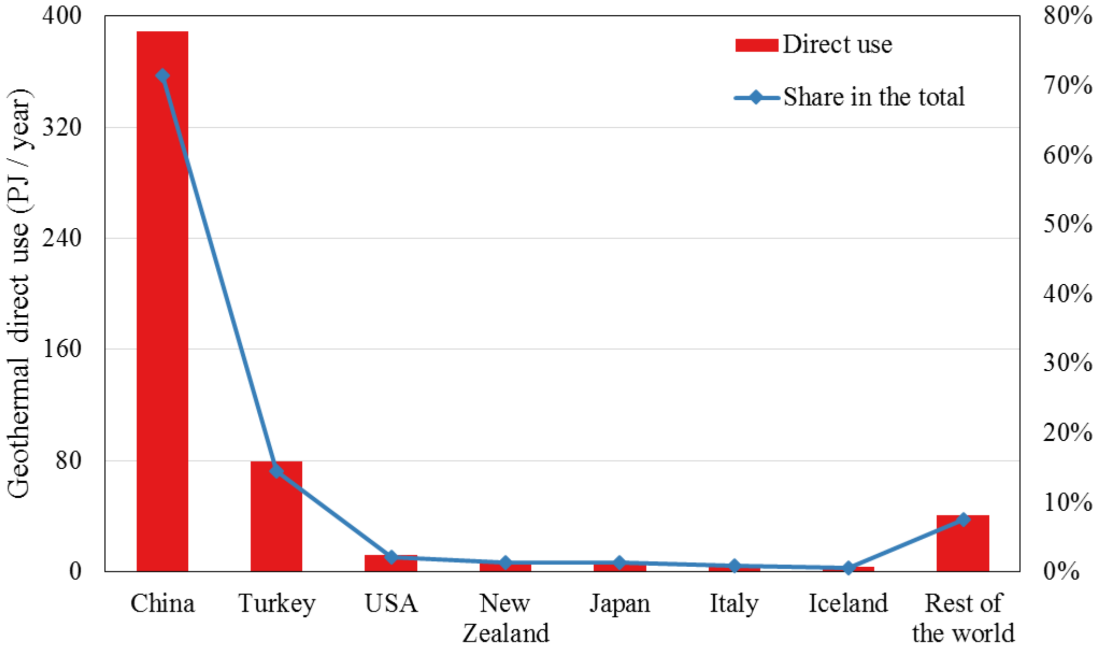


Fig. 2 Geothermal direct utilization in main utilizing countries (2017)

2. Environmental risks of geothermal energy development

A number of previous studies have sought to provide a qualitative analytical overview of the environmental impacts of geothermal development (DiPippo, 1991; Bonte et al., 2011; Bayer et al., 2013; Possemiers et al., 2014). Different from these studies, the present study endeavours to use actual data on geothermal projects, focusing on quantifiable data. Meanwhile, to better describe these environmental risks, they are classified into three groups based on their spatial distribution namely: subsurface environmental risks, surface environmental risks, and atmospheric environmental risks (Table 1). Here, there is no distinction made between different geothermal systems and technologies. This is because the classification of their environmental risks is roughly the same, although risk levels vary.

Table 1 Classification of geothermal environmental risks in this study

Classification	Secondary Classification	Details
Subsurface environmental risks	Hydrological risks	Groundwater levels, temperature, chemicals, and drinking water production
	Geological risks	Ground deformation and subsidence, fault reactivation and induced micro-seismicity
	Microbiological risks	Diversity of microbial communities
Surface environmental risks	--	Land use, landscape, surface water pollution (river, lake), agriculture and ecosystem destruction
Air risks	--	Air pollution, noise

2.1 Subsurface environmental risks

The subsurface environmental risks arising from geothermal energy development were distinguished as hydrological, geological, and microbiological risks (Table 2). Through reviewing relevant literature, we found that some environmental effects are unlikely to occur but may generate far-reaching influences on human health, ecology, and the economy. Therefore, they have high associated risks. However, other effects have a high probability of occurrence but only incur minor effects, hence, they are seen to have low risks (Bonte et al., 2011). Table 2 compares the occurrence rates and risks of different groups of subsurface environmental impacts.

Table 2 Comparison of subsurface environmental risks by geothermal energy (Bonte et al., 2011)

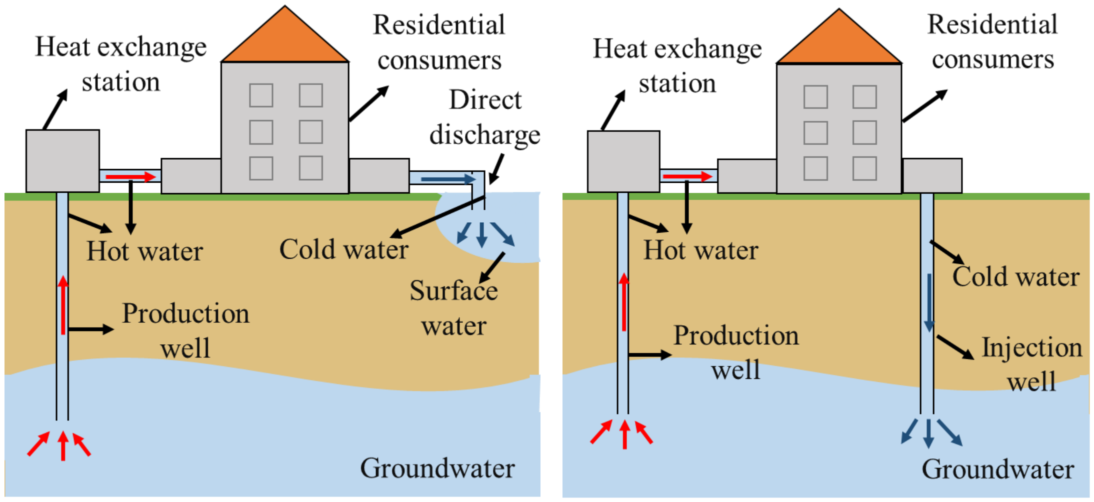
Environmental risks	**Conditions of occurrence**	**Probability of occurrence**	**Consequences**	**Risk level**
Hydrological risks				
Changing water levels	Single-well geothermal system	High	Water shortage for agriculture and production	Low
Cross-aquifer contaminant	Improperly plugged well or inadequate clay layer	Moderate	Increasing vulnerability, pollution	High
Changing groundwater chemistry	Temperature variation in shallow and deep geothermal systems	Moderate	Corrosion, nutrients	Moderate
Geological risks				
Ground deformation and subsidence	Pressure drop in middle and deep geothermal	Moderate	Ground subsidence, earthquake,	High

	systems			
Fault reactivation	High fluid pressure in middle and deep geothermal systems	Low	enormous damage to the society and economy	High
Induced micro-seismicity		Low		High
Microbiological risks				
Changing the microbiological population and biodegradation rate	Temperature variation in shallow and deep geothermal systems	High	Nutrients and anaerobic corrosion	Low
Introduction or mobilization of pathogens		Low	Pathogens	Low

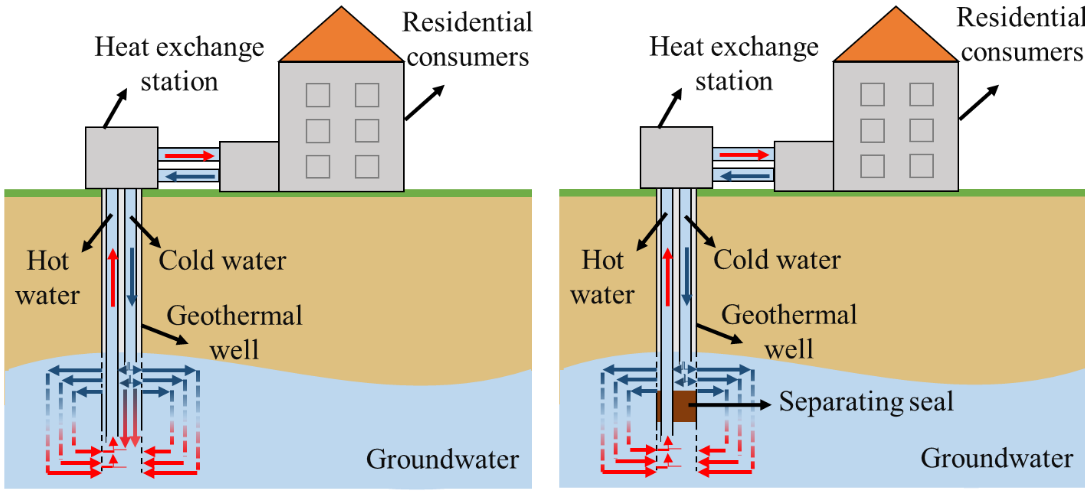
2.1.1 Hydrological risks

Hydrological risks caused by geothermal energy generally involve groundwater quality and quantity including: groundwater levels, temperature, chemical components, and drinking water production (Bonte et al., 2011). The influence on the groundwater level depends mostly on the type of geothermal system. Hydrothermal systems can be divided into four categories according to the discharge methods for extracted groundwater (Wu et al., 2015). Single-well extraction systems can result in a direct decline in groundwater level because they release the pumped water on the surface rather than reinjecting (Fig. 3). The impacts of the remaining three system types on the groundwater level depend on the method of recharge. If the systems can return the same volume of water as extracted, the groundwater level maintains constant. However, even sophisticated design and engineering will not return precisely the same amount as was pumped out (Orio et al., 2005).

As for the impacts on groundwater temperature, a survey of 67 aquifer thermal energy storage systems found that almost none of them maintained a thermal equilibrium during the period of geothermal production. This observation indicated that geothermal energy development does affect groundwater temperature (IF Technology, 2007). The groundwater temperature can be lowered by as much as 9 ℃ over five years if geothermal energy is used only for heating, while it could increase by 14-25 ℃ in the cooling applications (Li et al., 2006). The temperature disturbances caused by geothermal energy use are far stronger than the natural variations in aquifers. These disturbances have an impact on the chemical composition and properties of groundwater, in particular, trace elements, pH and dissolved organic carbon (Brons et al., 1991; Jesubek et al., 2013; Bonte et al., 2013a). Based on existing literature, Table 3 lists the temperature-induced impacts of geothermal energy production on underground water chemistry. For example, high geothermal well temperatures (> 25℃) can lead to a significant increase in groundwater concentrations of substances such as As.



(a) Single-well extraction system (b) Two-well circulation system



(c) Standing column well system (d) Single-well circulation system

Fig. 3 Schematic diagrams of hydrothermal type geothermal systems

Geothermal wells which have been improperly plugged or have a thin clay layer may create vertical communication paths for contaminants between separated water-bearing zones (Mayo, 2010; García-Gil et al., 2016). Contaminants in shallow aquifers can flow down along the well casings to deeper aquifers (Fig. 4) (García-Gil et al., 2016). A rise in groundwater temperature may mobilize immovable contaminants or increase the toxicity of pollutants by increasing solubility and reducing adsorption (Knauss et al., 2000; Noyes et al., 2009). Moreover, with the promotion of shallow geothermal applications, the geothermal systems are increasingly being built near drinking water aquifers. As a result, the risks of public water supply are raised (Ferguson, 2009; Haehnlein et al., 2010). The use of geothermal energy also affects the location of the groundwater extraction wells (Bonte et al., 2011).

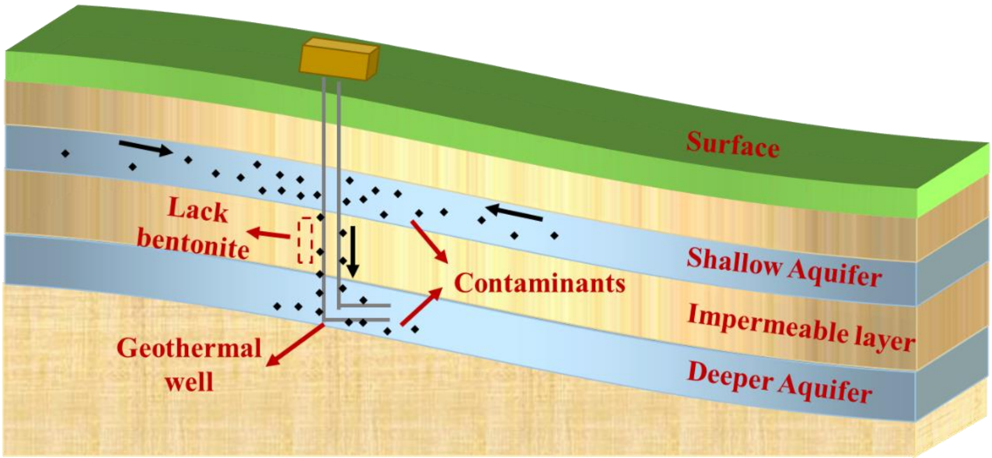


Fig. 4 Schematic diagram of cross-contamination of separating aquifers through a geothermal well

Table 3 Impacts of geothermal use on groundwater chemistry

Items	Temperature	Direct impacts	Indirect impacts	Studies
Trace elements				
As	> 25 °C	+	Causes arsenic poisoning	Brons et al., 1991; Koç, 2007; Bonte et al., 2013a
Ca	> 45 °C	-	Increased risk of cardiovascular disease	
Mg	> 60 °C	-		
B, F, K, P, Si, and V,	60 °C	+	Cause pollution; Reduce agricultural productivity	
Dissolved organic carbon	60 ˚C	+	Accelerate biodegradation and require discolouration treatment before drinking water supply	Wallage et al., 2006; Bonte et al., 2013a
Total inorganic carbon	70 °C	-	Release carbon dioxide and accelerate the warming effect	Jesubek et al., 2013
pH	10 °C	-	Influence the solubility of carbonates	Inskeep, 1986; Bonte et al., 2013a
	10 - 40 °C	±		
	60 °C	+		
	70 °C	-		
Chemical oxygen demand	> 45 °C	+	Causes organic pollution	Brons et al., 1991
Inorganic salts				
Nitrate	>10 °C	-	Releases air pollutants, such as NO_2, SO_2	Jesubek et al., 2013
Sulphate	70 °C	-		
Heavy metals				
Pb, Mo, Cr, Ni	70 °C	+	Threat to public health and the environment	Jesubek et al., 2013; García-Gil et al., 2016
Toxicity	> 25 °C	+	Increase the toxicity of drinking water	Noyes et al., 2009

Direct impacts on groundwater chemistry: increased groundwater temperature will have positive impacts (+), negative impacts (-), and insignificant impacts (±).

2.1.2 Geological risks

Geothermal energy development is often accompanied by changes in pressure or temperature in the geothermal reservoir, resulting in ground deformation and subsidence, fault reactivation and micro-seismicity in the utilized geothermal areas, especially in regions adopting enhanced geothermal systems (EGS) (Jeanne et al., 2015). EGS is used to extract heat from hot dry rocks without natural fracturing, to reduce the dependence on natural geothermal reservoirs (Fig. 5). The depth of hot dry rock is generally over 3 km, and its naturally low permeability can be increased by hydraulic fracturing (Olasolo et al., 2016; Lu, 2018).

Ground deformation is a common phenomenon in regions with established EGS. A study on geothermal power plants at Reykjanes, Iceland, which began to run in 2006, found that rocks near the geothermal area underwent a significant contraction, due to reservoir pressure decline (Parks et al., 2018). Moreover, studies of ground deformation and subsidence resulting from geothermal energy utilization in Krafla region in North Iceland and Hengill region in Southwest Iceland revealed ground subsidence of between 5 mm and 20 mm per year (Vasco et al., 2013; Drouin et al., 2017).

The use of geothermal energy can also induce fault reactivation and seismicity because injected fluids can result in lower rock temperature and higher pore pressure (Jeanne et al., 2014; Johnson et al., 2016). The potential for fault reactivation in a geothermal reservoir in the Northeast German Basin was assessed through a slip tendency analysis. They found that high fluid pressures (> 100 MPa) can reactivate potential normal and strike-slip faults (Moeck et al., 2009). The higher the temperature differences between the injected water and surrounding rocks, the higher the thermal shrinkage pressure, and therefore the more significant the magnitude of the seismic events (Gan and Elsworth, 2014).

Based on seismicity rates in Geysers geothermal field in California, the micro-seismicity in deep intervals greater than 3 km often occurs within 2-5 months after water injection. In contrast, there is almost no time difference between the micro-seismicity and water injection at shallow depths of lower than 2 km (Johnson et al., 2016). In St. Gallen, Switzerland, deep geothermal development projects led to a 3.5-magnitude earthquake (Edwards et al., 2015). Moreover, EGS at depths of about 5 km underneath the city of Basel, Switzerland, were closed on account of unaffordable risks related to seismic activities (Baisch et al., 2009). More examples are presented in Table 4.

Seismic hazards resulting from geothermal energy use may cause tremendous damage, and the scale of losses varies based on the geological structure, geothermal system, and local vulnerability. For example, the seismicity in Basel was widely felt, and caused damage of about 7 million

Swiss Francs, while little damage was reported as being caused by the seismic activities in St. Gallen (Baisch et al., 2009; Edwards et al., 2015). Accordingly, selecting proper assessment methods for induced seismicity hazards is crucial for promoting geothermal energy development. Relevant discussion and literature will be presented in Section 3.1.

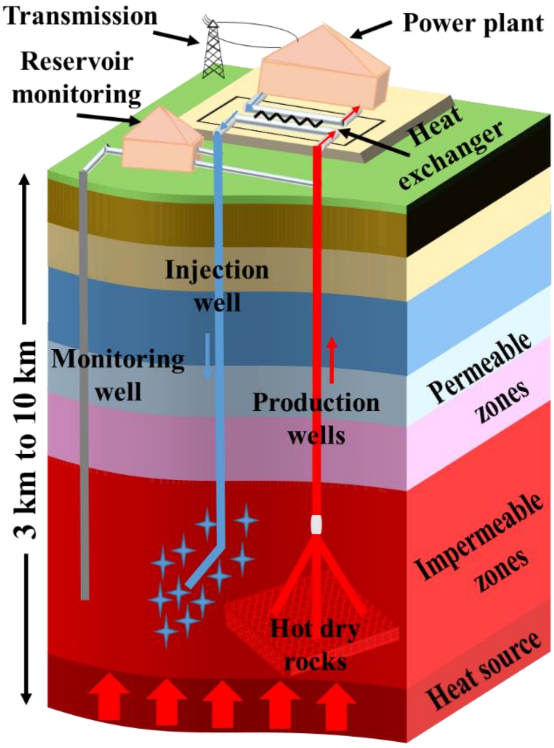


Fig. 5 Schematic diagram of EGS

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Table 4 Geological risks of geothermal energy development

Region / Country	**Temperature**	**Depth**	**Usage**	**Impacts on geology**	**Attributes**	**Reference**
Northeast German Basin	150 °C	3.9-4.4 km	In-situ geothermal laboratory	High fluid pressure (> 100 MPa) can reactivate potential strike-slip and / or normal fault.	Pore pressure increases.	Moeck et al., 2009; Reinsch et al., 2015
Reykjanes, Iceland	350 °C	> 1.75 km	Power generation (100 MWe)	The region underwent a contraction, and the deformation area is 4 km long and 2.5 km wide	Pressure drop in the geothermal reservoir.	Axelsson et al., 2015; Parks et al., 2018
Krafla, Iceland	> 200 °C	≤ 2 km	Power generation (60 MWe)	The subsidence between 5 mm and 7 mm per year occurred over a 5 km wide area.	Thermal contraction of bedrock.	Drouin et al., 2007
Hengill, Iceland	275 °C	≤ 3 km	Power generation (210 MWe)	The subsidence of up to 20 mm per year occurred over a 2 km wide area.	Pressure drawdown within the geothermal reservoir.	Gunnarsson et al., 2010; Juncu et al., 2017;
California, USA	280 - 350 °C	≤ 4 km	Power generation (1541 MWe)	The region existed subsidence of roughly 5 cm per year and earthquakes caused by injected fluids.	Pressure and thermal changes.	Goyal and Conant, 2010; Vasco et al., 2013; Johnson et al., 2016
Basel, Switzerland	190 °C	5 km	Power	A micro-seismicity with $M_L = 3.4 \pm 0.1$	Unfavorable location of	Häring et

			generation	(Mw = 3.2 ± 0.1) was triggered in 2006, and caused damage of about 7 million CHF.	geothermal systems in crystalline basement.	al., 2008; Folesky et al., 2016
St. Gallen, Switzerland	130 - 150 °C	4.5 km	District heating	A macro-seismicity with $M_L = 3.5 \pm 0.1$ (Mw = 3.3–3.5 ± 0.1), was induced in 2013.	Pressure and temperature changes.	Edwards et al., 2015
Olkaria, Kenya	< 340 °C	3 km	Power generation (513.8 MWe)	A subsidence rate from 7 mm to 13 mm per year was observed in this region.	Pressure and temperature changes.	Karingithi et al., 2010; Koros and Agustin, 2017

Noted: M_L indicates the local magnitude; M_w indicates the moment magnitude.

2.1.3 Microbiological risks

Underground microbial diversity is a precious, under-recognised asset, especially for subsurface nutrient dynamics. Multiple studies have analyzed the microbial diversity in geothermal zones. For instance, the microbial community structures of geothermal fields and the surrounding areas in Iceland varied with temperature, especially for bacterial diversities (Skirnisdottir et al., 2000; Hjorleifsdottir et al., 2001; Tobler and Benning, 2011). Temperature variations of 5-80 °C can also affect oxidation-reduction processes in aquifers. Studies have shown that thermophilic microbial communities specialized in fermentation and sulfate reduction, appeared when the temperature rose higher than 45 °C, resulting in pH decrease and anaerobic corrosion (Bonte et al., 2013b; Nogara and Zarrouk, 2018).

Moreover, based on collected data from 925 geothermal springs in New Zealand, claims that microbial diversity was significantly influenced by pH at temperatures of less than 70 °C, it was shown to be primarily affected at temperatures above 70 °C (Power et al., 2018). Studies have proposed three biological variables to quantify microbial diversity in shallow geothermal aquifers. These variables include total bacterial abundances (BAs), bacterial carbon productivity (BCP), and bacterial extracellular phosphatase activity (EPA). The results showed that EPA was positively correlated to temperature (Brielmann et al., 2009). However, evidence of introducing pathogens to the groundwater has not been observed. As such, further research on this field is needed (Bonte et al., 2013b).

2.2 Surface environmental risks

Geothermal energy development also affects the surface environment, by direct and indirect land use and changes in the landscape and ecosystem. Land use issues severely restrict the development of geothermal energy in some countries where new geothermal projects are usually located in or near national parks or tourist areas, although geothermal power plants require less land than other renewable energy (Goldstein et al., 2011; DiPippo, 2016). Table 5 presents the infrastructure footprints for typical geothermal power plants. This infrastructure includes drilling platforms, pipelines, roads, fluid separators, heat exchange stations, and power stations. Based on the above considerations, the land use of a geothermal power plant is about 1,200-7,500 m^2/MWe.

Land resources can also be affected by geothermal projects, especially in tropical areas, and this has become a growing concern for countries with abundant geothermal resources (Quy et al., 2000). The areas of these projects encompass geothermal power plants and buildings, exploratory and production wells, and auxiliary facilities, all of which influence the landscape pattern of the surrounding areas (Griffith et al., 2002). In the geothermal energy development areas of Hawaii, the size of vegetation communities was seen to decline, which would have further consequences for other forms of life (Griffith et al., 2002). Moreover, a survey on Mount Kilauea revealed that geothermal development attracted exotic ants. These newcomers affected other fauna by directly attacking hatchlings or newborn mammals and eliminating invertebrate prey of certain species (Wetterer, 1998).

Geothermal energy development can also cause soil warming and surface water pollution. Soil warming influences the fitness and trait expression of plants and causes genetically based variations, particularly for pollination and flowering (Valdés et al., 2019). Through investigating the structure of primary producers, a 50-80% increase of bryophyte cover was observed in warmer geothermal streams, as well as a lower concentration of chlorophyll-a (Gudmundsdottir et al., 2011; O'Gorman et al., 2014;). Moreover, geothermal wastewater discharged to the surface can adversely affect rivers, lakes, and marine environments. It was reported that annual emissions of wastewater to the Büyük Menderes River by a geothermal power plant in Turkey were about 7.4 million tonnes (Yildirim and Simsek, 2003). Such wastewater generally includes geothermal water extracted from the underground and fluids used in wells drilling, completion, and cementation (Finster et al., 2015). Furthermore, the Great Menderes River in Turkey was polluted by geothermal wastewater containing significant concentrations of the element boron. This form of pollution could severely impact 13,000 hectares of irrigated agricultural land around the Menderes Basin (Koç, 2007). More broadly, complex chemical properties render geothermal wastewater a potential source of soil, water and wetland pollution (Clark et al, 2011; Reeves et al., 2018).

Table 5 Land use for typical geothermal power plants (DiPippo, 2016)

Type of power plant	**Land use**	
	m^2 / MWe	**m^2 / GWh / yr**
56 MWe geothermal flash plant (including wells, pipes)	7,460	900
110 MWe geothermal flash plants (excluding wells)	1,260	160
20 MWe geothermal binary plant (excluding wells)	1,415	170
49 MWe geothermal Flash-Crystallizer/Reactor- Clarifier plant (excluding wells)	2,290	290

2.3 Air environmental risks

The literature on the environmental advantages of geothermal energy in mitigating global warming has tended to overlook its contribution to air pollution (Ármannsson, 2018). Geological fluids sometimes contain a certain proportion of dissolved NCGs (Clark et al, 2011). These NCGs usually consist of carbon dioxide, hydrogen sulfide, helium, hydrogen, argon, oxygen, nitrogen, and methane. They are often released to the atmosphere when steam is flushed, except for the hydrogen sulfide, to maintain operational efficiency (Clark et al, 2011). Typical NCG concentrations range from 0.5% to 1.0% of the steam generated by geothermal power plants (DiPippo, 2016), while other research indicated that NCG concentrations could be broader - from 0.2% to 1.8% (Goldsmith, 1971). Table 6 presents data regarding NCG concentrations in production fluids in geothermal fields in Nevada and Utah, USA, collected and compiled by the Geothermal Data Repository (https://gdr.openei.org) in 2017. As another impact, geothermal power plants can also introduce noise of 71-83 dB, exceeding community noise standards of 55 dB for outdoor spaces and 70 dB for industrial districts (Shortall et al., 2015).

These released NCGs and unwanted noise may cause public nuisance or health concerns. Many geothermal areas are thickly populated, and some of them are adjacent to metropolises. As a consequence, approximately 500 million people were indicated to be living within the influence area of volcanos and geothermal areas (Hansell et al., 2006). It is known that 30-minutes exposure to 500 ppm of hydrogen sulfide can cause headache, dizziness, and diarrhea (USGS, 2017). Furthermore, more prolonged exposure to high levels of hydrogen sulfide can lead to coma and eventually death from poisoning (Beaubien et al., 2003; Hansell and Oppenheimer, 2004). Apart from outdoor air quality, geothermal development and application can also result in severe indoor air quality problems (Durand, 2006).

Table 6 Main non-condensable gases in geothermal steam

Constituents	**Unit**	**Beowawe, NV**[a]	**Dixie Valley, NV**[a]		**Thermo, UT**[b]			
		Gas bottle 1	**Gas bottle 1**	**Gas bottle 2**	**Gas bottle 1**	**Gas bottle 2**	**Gas bottle 3**	**Gas bottle 4**
Carbon Dioxide (CO_2)	mmol/mol	ND[c]	ND	ND	1.053883	0.826235	1.020808	0.605075
Hydrogen Sulfide (H_2S)	mmol/mol	ND	ND	ND	0.196067	0.209004	0.224076	0.201692
Helium (He)	mmol/mol	0.000080	0.000056	0.000045	0.000027	0.000017	0.000015	0.000021
Hydrogen (H_2)	mmol/mol	0.000216	0.000335	0.000257	0.000052	0.000036	0.000040	0.000054
Argon (Ar)	mmol/mol	0.002626	0.001446	0.001146	0.000430	0.001846	0.000497	0.001948
Oxygen (O_2)	mmol/mol	0.008333	0.000004	0.000004	0.001663	0.039728	0.008085	0.041848
Nitrogen (N_2)	mmol/mol	0.122888	0.053759	0.046033	0.016609	0.197694	0.045323	0.213621
Methane (CH_4)	mmol/mol	0.004106	0.006478	0.004967	0.000107	0.000367	0.000060	0.000047

[a] Gas examples were collected and analyzed from geothermal fields in Beowawe and Dixie Valley, Nevada, USA.

[b] Gas examples were collected and analyzed from geothermal fields in Thermo, Utah, USA.

[c] ND indicates that there was no data for this constituent.

3. Quantitative assessment of the environmental risks

Negative environmental impacts of geothermal energy may have socio-economic consequences for the local population or even the nation. For instance, geothermal power generation in Kenya caused conflict within the local Maasai community because it had adverse effects on the area of available grazing land (Mariita, 2002). Accordingly, it is of great importance to measure and quantify possible losses in human health, ecology and the economy. However, existing environmental risk assessment of geothermal energy identifies environmental hazards but does not measure their losses effectively or holistically (Liu and Ramirez, 2017). As such, this section addresses the issue of how to predict and quantify these losses caused by geothermal environmental risks. Moreover, geological models for predicting the occurrence, intensity and damage of the geological hazard are also introduced.

3.1 Assessment of geological hazard

To predict and manage the geological hazard arising from geothermal energy, a traffic-light system has been widely applied in recent experiments and has been used to decide when to stop or close geothermal projects (Giardini, 2009; Convertito et al., 2012). Fig. 6 presents the structure of the traffic-light system, which consists of three steps: i) to predict the occurrence rate of geological hazards during the geothermal utilization process; ii) to identify and classify the intensity of geological hazards; iii) to define scope and extent of damage caused by geological hazards. There are also other important factors, such as coping strategies and technological advances (Bommer et al., 2006). However, this section is only structured around the above three steps.

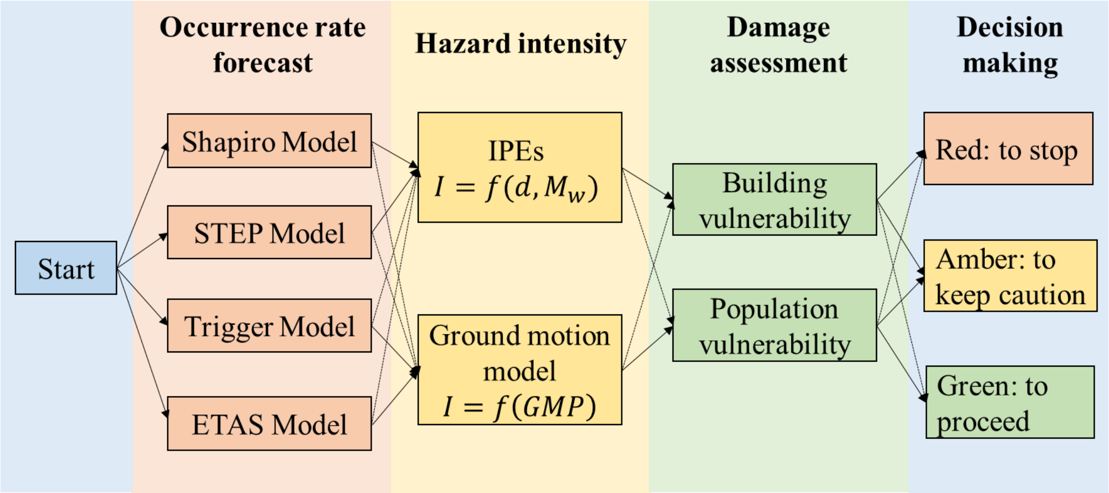


Fig. 6 The logical structure of traffic-light system in seismic hazard assessment

3.1.1 Occurrence of geological hazards

Geological hazards such as small earthquakes (-3<M<2) in geothermal reservoirs are considered to be a result of fluid injection (Rothert and Shapiro, 2003). Through continuously observing two different locations, the probability of occurrence of an earthquake was positively related to the injection time given the same magnitude and injection pressure (Shapiro et al., 2007). Similarly, the frequency of seismic events was proportional to the amount of injected fluids (Shapiro et al., 2010). However, the above models did not consider the size of the micro-seismicity events nor other source parameters such as stress drop. Fortunately, other studies have established a link between the occurrence of seismic hazards and geo-mechanical properties, including pore-pressure perturbations, distance, and magnitude (Goertz-Allmann and Wiemer, 2013).

Seismic shocks can be classified as either primary or induced shocks. Following the Gutenberg-Richter law, the short term earthquake probabilities (STEP) model was developed and applied in predicting the occurrence of aftershocks (Gerstenberger et al., 2005; Bachmann et al., 2011). The trigger model was also used to depict the aftershocks generated by given primary events (main shocks) (Lomnitz and Nava, 1983). It assumed that the occurrence of an aftershock (with a magnitude above a given level) induced by the main shock at time t_0, was a conditional probability. In other words, the original trigger model was based on known main shocks, which was inconsistent with the actual situation. To consider more general cases, scholars have proposed a restricted trigger model, in which the occurrence time and magnitude of main shocks are both unknown (Ogata, 1988). Based on the trigger model, the Epidemic-Type Aftershock Sequence (ETAS) model was developed. ETAS takes a stationary distribution of main shocks and occurrence rates of all shocks (including primary and induced shocks) into account (Ogata, 1988). However, the original ETAS model assumes a constant background rate of events, while the extended ETAS model defines a variable background rate (Bachmann et al., 2011). To conclude, the Shapiro model, STEP, trigger model, and ETAS have been extensively used to forecast the occurrence of induced seismicity, with details listed in Table 7.

Table 7 Relevant models for earthquake occurrence

Models	**Equations**	**References**
The Shapiro Model	$N(t)={q\xi t}/{C_{\max}}$, with ${q\xi}/{C_{\max}}$ is the event rate, and t is injection time.	Shapiro et al., 2007
	$N(t)={NQ_i(t)}/{C_{\max}S}$, with N, $C_{\max}$, and S are parameters, and $Q_i(t)$ is a cumulative injected fluid volume.	Shapiro et al., 2010
Short Term Earthquake Probabilities (STEP) Model	$n_a(t)=10^{a'+b(M_0-M_r)}/(t+c)^p$, with $n(t)$ is the occurrence rate of aftershocks with a magnitude larger than M_r, t days after a major shocks of magnitude M_0.	Gerstenberger et al., 2005; Bachmann et al., 2011
Trigger Model	$\sigma_{t_0}(t)=\begin{cases}\theta\cdot f\left(t-t_0\right), & t\geq t_0\\ 0, & t<t_0\end{cases}$, with $\sigma_{t_0}(t)$ is the event rate of aftershocks, $\int_0^\infty f(t)dt=1$ and θ is the average number of aftershocks induced by a primary shock.	Lomnitz and Nava, 1983
	$\sigma_a(t)=e^{\beta(m_i^c-M_r)}\cdot\sum_{t_i^c<t} g\left(t-t_i^c\right)$, with t_i^c and m_i^c are the timing and magnitude of the primary shocks, β and M_r are parameters.	Ogata, 1988
ETAS Model	$\varpi(t)=\mu+\sum_{t_i^c<t}\sigma_{a,\,i}\left(t\right)$, with $\varpi(t)$ is the event rate of total shocks, and μ is the event rate of primary shocks.	Hainzl and Ogata, 2005
	$\varpi(t)=\mu(t)+\sum_{t_i^c<t}\sigma_{a,\,i}\left(t\right)$, with $\mu(t)$ is non-stationary and associated with injection condition.	Bachmann et al., 2011;

3.1.2 Intensity of geological hazards

There are many macroseismic intensity scales, but only eight have been widely adopted. These include the European Macroseismic Scale (EMS-98), the Mercalli-Cancani-Sieberg (MCS) scale, the Modified Mercalli Intensity (MMI) scale, the Medvedev-Sponheuer-Karník (MSK) scale, and the Japan Meteorological Agency scale (Musson et al., 2010). Although different intensity scales have different standards and degrees, the conversion between the major intensity scales has been established (Musson et al., 2010). More recently, studies have paid increasing attention to earthquake intensity prediction, as losses to society and the public can be estimated based on the intensity values (Musson et al., 2010).

Many studies have constructed intensity prediction equations (IPEs) based on observed intensity data in different regions and countries. According to the Macro-seismic Earthquake Catalogue of Switzerland (MECOS), a linear forecasting model of hazard intensity was proposed with two independent parameters of magnitude and distance considered (Alvarez-Rubio et al., 2012; Fäh et al., 2003). Furthermore, a logarithmic relationship between the intensity and distance was obtained (Fäh et al., 2011). On the basis of global macro-seismic intensity observations, the IPEs were modified to predict earthquakes with moment magnitudes of 5.0-7.9 and intensities of greater than degree II for distances of less than 300 km from the active crustal region (Allen et al., 2012).

From the perspective of ground motion, another intensity prediction model has been built using motion parameters as independent variables (Wald et al., 1999; Atkinson and Kaka, 2007). Usual motion parameters include peak ground acceleration (PGA) and peak ground velocity (PGV). The relationship between the PGV and events intensities between II and VII on the EMS-98 scale was observed (Kästli and Fäh, 2006), while the ties for intensities between IV and IX on the MCS scale was also obtained (Facciolo and Cauzzi, 2006). Moreover, the MMI-PGV correlation had less systematic errors than PGA based on Iranian recorded ground shaking (Yaghmaei-Sabegh et al., 2011). Such a method also has a full application to the geothermal field. For example, a combination ground motion model and geophysical 3-D model was applied to simulate seismic intensities in the geothermal reservoir of the Basel region, Switzerland (Ripperger et al., 2009).

Table 8 compares the prediction results of IPEs and ground motion models. It is found that there are differences between the results of these two models and actual observations, and it is hard to say which one is better. For instance, the mean regression errors for PGA & PGV were both higher than for IPE when predicting earthquake intensity in Turkey, but lower when predicting intensity in Italy (Sørensen et al., 2008). Many factors affect the accuracy and reliability of these models, including intensity scales, magnitude, distance, and depth. For example, the discrepancy between the MSK-PGV and MMI-PGV relationships of Californian earthquake observations was caused by the intrinsic differences between the intensity scales (Facciolo and Cauzzi, 2006). The limitations of models based on ground motion parameters and MMI intensities were discussed by Linkimer (2008).

Table 8 Comparison between intensity estimates of IPEs and ground motion models

Studies	**Data source**	**Intensity**	**Moment magnitude**	**Depth (km)**	**Distance (km)**	**Comparison**
Facciolo and Cauzzi, 2006	Earthquake catalogue, Italy	I_{MCS} = IV-IX	3.8-7.4	2-20	1.5-71	The intensity estimates based on ground motion parameters are less accurate than IPEs.
Sørensen et al., 2008	Marmara, Turkey	I_{MMI} = V-X	5.9-7.4	--	0-335	The mean regression errors by PGA & PGV are both higher than IPEs, but the adjusted model of PGA is better than IPEs, not true for adjusted PGV model.
	Naples, Italy	I_{MMI}=III-XI	6.3-7.0	6.3-15.6	0-660	The mean regression errors by PGA & PGV are both lower than IPEs.
	Vrancea, Romania	I_{MMI}=V-VIII	6.4-7.7	79-150	0-500	The mean regression errors by PGV and adjusted PGA model are lower than IPEs.
Allen et al., 2012	Assumption	I_{MMI} = IV-X	5.0-7.9	5	0-300	The regression errors by combined ground motion models are larger than IPEs, but the combined curves have a clear inflection point, consistent with a transition from non-damaging effects to actual damages.
Mignan et al., 2015	Basel & St Gallen, Switzerland	$I_{EMS\text{-}98}$ = I-V	3.2-3.3	4.5-4.7	0-80	The predicted intensities from ground motion methods are basically consistent with IPEs results.
Zare, 2017	Iranian Plateau	I_{MMI} =V-X	4.6-7.6	--	0-300	The MMI intensity is more correlated with the PGA, and the mean residual based on MMI-PGA is less than MMI-Magnitude relationship.

3.1.3 Damage from geological hazards

Damage from geological hazards to local buildings or population is generally divided into six levels: none, minor, moderate, heavy, very heavy, and completely damaged (Tables 9 and 10). Existing assessment models for estimating the damage to buildings and population are shown in Table 11. The damage scope and extent of geological hazards depend on various factors besides the magnitude of earthquakes. For example, a comparison of earthquakes with the same scale in Iran and Turkey revealed more severe destruction in Iran due to weaker buildings. Therefore, the damage estimation for geological hazards requires considerations of building vulnerability and population vulnerability (JICA, 2000).

Building vulnerability varies according to building types, materials, and height. By investigating damages of historical earthquakes in Iran on different types of buildings, fragility curves of six building types were obtained. The results showed that reinforced concrete structures suffered the least damage, while mud buildings were the most vulnerable (Karimzadeh et al., 2014). Substantial advances have been made by recent research with respect to building vulnerability assessment (Silva et al., 2014; Silva et al., 2015). One such model, a probabilistic displacement-based model, was developed to estimate earthquake loss. This model considers uncertainties in the properties of the building and assumes the earthquake damages are related to the building height (Crowley et al., 2004). Meanwhile, the critical issues in existing building vulnerability evaluation were argued by Silva (2018). Notably, building loss assessments overlook the impacts of soil condition on the spectral acceleration (Stewart et al., 2013).

Population vulnerability can be defined as the degree of population loss incurred by earthquakes (Karimzadeh et al., 2014). Population losses in an earthquake are associated with many factors, such as population density, occurrence time (day or night), building types, and available rescue countermeasures (Xu et al., 2016). Statistically, 75% of population deaths in an earthquake have been caused by building destruction or collapse (Coburn and Spence, 2002). Accordingly, population losses are generally determined by the number of people inside each type of buildings and probabilities of being dead/ hospitalized/ injured/ not hospitalized/and not injured (Hassanzadeh et al., 2013). Moreover, population loss evaluation approaches based on spatial modeling (Ara, 2014), and non-linear regression models also exist (Xu et al., 2016).

Table 9 Damage classification of buildings based on previous studies

Damage level	**Description**	**Damage percentage**			
		Cochrane and Schaad, 1992	Baisch et al., 2009		Hassanzadeh et al., 2013
			RISK-UE	SERIANEX	
None	No damage	0%	0%	0%	0-2%
Minor	Negligible to slight damage or very tiny cracks	5%	1%	2%	3-10%
Moderate	Slight structural (5-20 mm cracks) and moderate nonstructural	20%	10%	15%	11-30%
Severe	Moderate structural (> 20 mm cracks) and heavy non-structural	58%	35%	55%	31-60%
Very heavy	Heavy structural (A part of the roof and one building's wall is destroyed) and very heavy non-structural	94%	75%	91%	61-80%
Completely damaged	Very heavy structural and partial or total collapse	100%	100%	100%	81-100%

Table 10 Classification of population damage based on previous studies (Hassanzadeh et al., 2013)

Type of damage	**Status of people**	**Percentage of damage**	**Type of damage**	**Status of people**	**Percentage of damage**
None	Dead	0	Heavy	Dead	13%
	Hospitalized	0		Hospitalized	17%
	Injured and not hospitalized	1%		Injured and not hospitalized	23%
	Not injured	99%		Not injured	47%
Minor	Dead	2%	Very heavy	Dead	16%

	Hospitalized	5%		Hospitalized	22%
	Injured and not hospitalized	9%		Injured and not hospitalized	38%
	Not injured	84%		Not injured	34%
Moderate	Dead	4%	Completely damaged	Dead	41%
	Hospitalized	9%		Hospitalized	16%
	Injured and not hospitalized	15%		Injured and not hospitalized	21%
	Not injured	72%		Not injured	22%

Table 11 Summary of published models for seismic building and population damage assessment

Name of model	**Developer**	**Type of analysis**	**Descriptions**	**Applications**	**References**
Prompt assessment of global earthquakes for response	U.S. Geological Survey	Deterministic, probabilistic	Assessing potential societal impacts including inferred vulnerability of the regional buildings and population exposed to severe ground shaking.	Global	Earle et al., 2009
Quake loss assessment for response and mitigation	International Centre for Earth Simulation	Deterministic, probabilistic near-real-time	Estimation earthquake loss in near real-time and scenario modes based on world data sets of population and building stocks.	Global	Trendafiloski et al., 2009
Hazard of United State	Federal Emergency Management Agency	Deterministic, probabilistic	Using Geographic Information System (GIS) to visualize spatial relationships between population and geographic assets and to estimate earthquake loss.	USA	FEMA, 2003
Earthquake loss estimation routine	Kandilli Observatory and Earthquake	Probabilistic, near-real-time	Incorporating both regional- and urban-scales in real-time estimations of rapid loss of earthquakes.	Euro-Mediterranean region	Hancilar et al., 2010

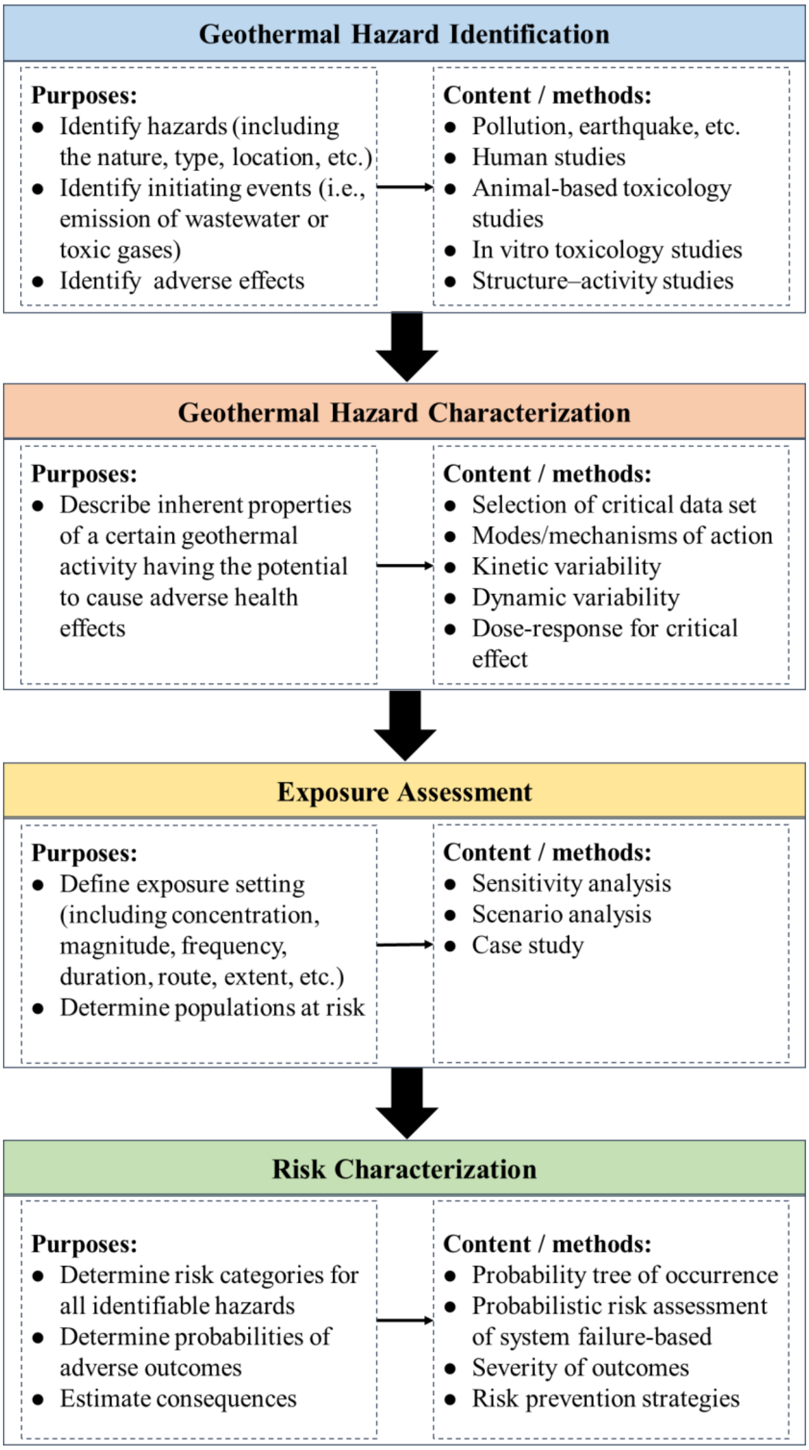
	Research Institute				
Seismic loss estimation using a logic tree approach	Norwegian Seismic Array	Deterministic, probabilistic, near-real-time	Implementing a logic tree-computation scheme and allowing users to define weighted input parameters and providing results within a confidence level.	Oslo, Norway	Molina et al., 2010
Earthquake risk management	Geoscience, Australia	Deterministic, probabilistic	Focusing on direct financial losses caused by building and contents damage exclude the damage caused by secondary hazards.	Australia	Robinson et al., 2005
Realtime assessment of earthquake disaster in Yokohama	Governments in Japan	Deterministic, real-time	Estimating the distribution of seismic intensity and damage to wooden buildings based on the GIS system, and gathering information of actual damages to roads within 60 minutes.	Yokohama, Japan	Ariki et al., 2004
Systemic seismic vulnerability and risk analysis	14 countries including USA, Japan, and Europe	Deterministic, probabilistic	Evaluating socio-economic seismic vulnerability, and considering buildings, transportation, utility networks and critical infrastructures in urban and regional scale.	Greece and Austria	0
People trapped in earthquakes	China earthquake administration	Deterministic	Estimating the distribution of the trapped population according to actual data of Ludian earthquake-hit areas in 2014.	China	Wei et al., 2017
Displacement-Based Earthquake Loss Assessment	University of Pavia and Imperial College	Deterministic, probabilistic	Using displacement response spectra to show a correlation between the frequency of the ground motion and fundamental period of the building under uncertainties.	Pakistan	Crowley et al., 2004

3.2 Assessment of health losses

Geothermal energy development may create health concerns for residents because of emissions of toxic substances or gases, such as heavy metals, radioactive materials, and hydrogen sulfide (Ellis, 1997). Wide-ranging studies in recent decades have employed epidemiological methods and statistical analysis to reveal the associations between human health and geothermal energy development. Table 12 summarizes previous studies on possible health effects of geothermal development, with methodologies and data identified. Most of these studies used statistical analysis and quantitative regression methods to illustrate the causal relationship between local population health and the chronic exposure to gases emitted by geothermal utilization. Their results showed various elevated rates of diseases of the respiratory, circulatory, urinary, and nervous systems as well as of the skin. However, there also exist a few studies that show no clear evidence of an association between human health and geothermal development. Such distinctions may be ascribed to the limitations of the model design and information asymmetry (Bates et al., 2015; Bates et al., 2017; Bustaffa et al., 2017).

There are, in addition, lessons from health risk assessment in other energy sectors, such as shale gas. Similar to geothermal energy, shale gas development also causes pollution of water, land and air, bringing harm to public health (Centner and Petetin, 2015). Some studies use inverse distance weighted number of shale gas wells or an “activity index” to define exposure (Stacy et al., 2015; Casey et al., 2016), while others adopt measures of health indices or birth weight (Hill, 2018). Xu et al. (2018) alternatively constructed a carcinogenic risk index and hazard index to evaluate the health risks of drilling workers.

In spite of so many early attempts, assessing health losses caused by geothermal energy development is still a major challenge being facing by governments and investors. So far, few studies have proposed a comprehensive and multi-disciplinary approach to overcome it. Fortunately, some scholars have distilled the necessary steps of human health assessment caused by natural hazards (Asante-Duah, 2017; WHO, 2010). On this basis, we propose an analytical framework for human health losses caused by geothermal energy development (Fig. 7). The framework comprises of four steps: i) geothermal hazard identification; ii) geothermal hazards characterization; iii) exposure assessment; iv) risk characterization (Asante-Duah, 2017; WHO, 2010).



Noted: Adapted from (WHO, 2010; Asante-Duah, 2017)

Fig. 7 Analytical framework of human health losses caused by geothermal energy development

Table 12 A summary of studies relating to possible health effects of geothermal development

Studies	Areas	Methodologies	Data / Indicators	Possible health effects
Gapas and Subida, 1995	Philippines	Cross-sectional occupational health survey and statistical analysis	**Samples:** 1,022 workers (624 geothermal and 398 hydro plant workers) **Indicators:** Respiratory symptoms, spirometric measurements, H_2S concentration	Results showed that respiratory complaints were significantly increased among geothermal workers, compared to hydro plant workers.
Sun and Ta, 1997	Tibet, China	Health survey	--	80% of the workers in Yangbajing geothermal power plants got trichomadesis, and 1/3 workers got a sickness of teeth erosion or losing in their thirties.
Bates et al., 1998	Rotorua, New Zealand	Statistical analysis	**Time range:** 1981-1990 **Indicators:** Standardized incidence ratio, morbidity;	Results showed elevated disease rates, notably nasal cancers, nervous system and eye diseases, induced by geothermal air pollution.
Bates et al., 2002	Rotorua, New Zealand	Poisson regression analysis	**Time range:** 1993-1996 **Indicators:** Standardized incidence ratio, morbidity;	Results showed that there existed exposure-response trends of hydrogen sulfide in the geothermal areas.
Minichilli et al., 2012	Tuscany, Italy	Epidemiologic investigation and statistical analysis	**Time range:** 1971-2006; **Samples:** about 43,000 inhabitants **Indicators:** Age-standardized mortality rate; age-standardized hospitalization rate;	Results showed a higher level of arsenic in drinking water distribution of geothermal areas, is a critical element of increased mortality and hospitalization.
Bates et al., 2015	Rotorua, New Zealand	Linear regression models and logistic regression models	**Time range:** 2008-2010 **Samples:** 1,204 subjects (18-65 years old)	Results showed no evidence for an increased risk of chronic obstructive pulmonary disease caused by geothermal development.

			Indicators: H_2S concentration, exposure metrics;	
Kristbjornsdottir et al., 2016	Iceland	Cox proportional hazard model and comparative analysis	**Time range:** 1981-2013 **Samples:** 7,511 individuals **Indicators:** Adjusted hazard ratio, personal characteristics (age, gender, education level)	Results showed higher cancer incidence in geothermal areas than the non-geothermal areas.
Bates et al., 2017	Rotorua, New Zealand	Linear multivariate regression models	**Samples:** 1,558 subjects (18-65 years old) **Indicators:** H_2S concentration, eyesight;	Results showed no evidence that the cataract was associated with geothermal development.
Bustaffa et al., 2017	Tuscany, Italy	Epidemiologic investigation and	**Time range:** 2003-2012 **Samples:** 40,462 subjects (19,678 men and 20,784 women); **Indicators:** Mortality	Results showed worse mortality in geothermal areas, especially for cancers in males and cerebrovascular disease in females, but the regression results were not significant.
Profili et al., 2018	Southern Tuscany, Italy	Competing-risks regression model (Fine and Gray, 1999)	**Time range:** 1999-2015 **Samples:** 900 samples (20-55 years old); **Indicators:** Standardized hospitalization ratio, hazard ratio;	Results showed various increased rates in circulatory system diseases and urinary system diseases, as well as a positive association between geothermal development and skin diseases.
Nuvolone et al., 2019	Tuscany, Italy	Dispersion modelling used to evaluate spatial variability of exposure to chronic levels of H_2S.	**Time range:** 1998-2016 **Samples:** 33,804 subjects (16,253 men and 17,451 women); **Indicators:** Standardized mortality ratios, standardized hospitalization ratios	Results showed a positive association between respiratory diseases and H_2S exposure, and no positive associations were found for cancer or cardiovascular diseases.

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3.3 Assessment of ecological losses

An ecological perspective for assessing environmental impacts of geothermal energy generally involves damages to ecosystem service functions, landscape and wilderness, soils and species, and cultural heritage. Ecosystem status and service functions of the environment is one of the essential determinants of human well-being (MEA, 2005). Understanding the relationship between ecosystem service functions and geothermal energy development is of crucial importance to the optimization of geothermal siting and system design. A recent study evaluated the environmental impacts of geothermal power plants from an ecosystem services perspective, with monetary and non-monetary approaches proposed (Cook et al., 2017). Based on the Common International Classification of Ecosystem Services (CICES) formed in 2013 (EEA, 2013), valuing ecosystem service impacts from geothermal energy can be conducted from three aspects of provisioning, regulation & maintenance and cultural services (Table 13) (Hastik et al., 2015).

Table 13 Classification of ecosystem service impacts in geothermal areas

CICES category	Division	Details
Provisioning services	Nutrition	Genetic resources and bio-chemicals, groundwater chemicals
	Materials	Freshwater supplies
	Energy	Mineral resources
Regulation & Maintenance services	Waste, toxics and other nuisances	Air and water purification and treatment, carbon capture
	Physical, chemical, biological conditions	Limited siting, seismic prevention, treatment of residual materials

Cultural services	Physical and intellectual interactions with ecosystems	Recreational amenity, archaeological heritage
	Spiritual, symbolic and other interactions with ecosystems	Aesthetics, spiritual enrichment, inspiration and other cultural associations

From the perspective of landscape pattern, landscape ecology approaches were proposed to assess the ecological impacts of energy development by stressing the effects of changes in spatial patterns on ecological processes (Turner, 1989). An integrated model of GIS and landscape ecology methods was used to examine the environmental impacts of geothermal energy. The model designed five landscape metrics, including dominance, contagion, spatial complexity, edge, and patch size, to quantify changes in landscape patterns. Assessing these changes is useful for understanding the potential influence on populations of native species (Griffith et al., 2002). However, a reasonable selection of landscape metrics is critically essential as certain landscape metrics may be redundant in some exceptional cases (O’Neill, 1996).

A multi-criteria analytical framework for the environmental impacts of geothermal energy from an ecological perspective has been put forward (Thórhallsdóttir, 2007). In the proposed framework, in addition to landscape and wilderness, four primary indicators were proposed: geology and hydrology, ecosystems and soils, species, and cultural heritage. Moreover, the analytical hierarchal process (AHP) approach was used to score and rank geothermal projects in Iceland. However, whether the results were convincing relied on data quality and quantity. These studies aside, there have been few investigations focusing on the environmental impacts of geothermal development from the ecological perspective. Therefore, efforts to fill in these knowledge gaps are an essential component of future research.

3.4 Assessment of economic losses

Geothermal energy development may have beneficial impacts on the local or regional economy by creating jobs for unemployed inhabitants, increasing tax revenues for improvements in infrastructure and utilities, and lowering energy costs (Lesser, 1994). However, it also causes economic losses. This section mainly focuses on economic losses caused by geothermal contamination, including water, soil, and air pollutions. Previously, many studies adopted life cycle assessment (LCA) to calculate greenhouse gas emissions and other pollutant discharges across the entire life cycle of a geothermal or shale gas well operation (Hondo, 2005; Prpich et al., 2016). LCA studies for environmental impacts of geothermal technologies usually provide similar characterization results, such as global warming potential, acidification potential, and eutrophication potential (Liu and Ramirez, 2017; Tomasini-Montenegro et al., 2017). However, few studies propose a reasonable methodology to evaluate possible economic losses from these results (Cook et al, 2017).

Despite deficiencies in studies concerning the assessment of

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economic losses due to geothermal pollution, there are a few methods to associate environmental pollution with economic development or growth. These methods could provide a reference for further quantification of geothermal environmental risks. Because of the characteristics of geothermal pollution, assessing economic losses can be evaluated from the following five aspects: agricultural production, drinking water shortage, public health, water/air treatment, and infrastructure corrosion and collapse. Economic losses from agricultural production decline depends on exposure-relative yield relationships and prices of main crops (Avnery et al., 2011). Common approaches to estimating economic losses caused by drinking water shortage and water/air pollution include market pricing or replacement costs (Krieger, 2001; Cook et al., 2007). As for public health, multiplying the aggregate medical cost of diseases related to geothermal pollution by a correlative coefficient represents medical expenses (Zhao et al., 2016; Guan et al., 2019). Finally, exposure-response relationships of buildings or infrastructure and maintenance or repair costs can be applied to estimate economic loss from infrastructure corrosion and collapse (Chen et al., 2013).

4. Discussions

4.1 Constraints

In summary, there are few studies on holistic quantitative evaluation of environmental risks of geothermal energy development. At the same

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time, a comprehensive and systematic assessment framework for geothermal development has not yet been developed. One primary reason is that each geothermal project is inherently unique, because of the specific characteristics in geology, hydrology, and chemistry of the different geothermal reservoirs. As a consequence, the environmental risks differ from case to case, which impedes the application and diffusion of relevant models and results. Secondly, some effects of geothermal environmental impacts have a long incubation period. For example, it took long periods to observe lung cancer caused by geothermal gas emissions. In other words, these effects are hidden in the short term, and therefore difficult to measure and quantify. The third point is that the boundary and value of potentially threatened environments, such as physical, socio-economic, and ecological environments, are hard to define and estimate. In an open system, geothermal wastes including gases, fluids, and solids can diffuse to all corners of a city and even adjacent cities. Fourthly, relevant data for geothermal development and operation are limited and may not be publicly available. The data shortage enhances the difficulty in analyzing the correlation between geothermal environmental impacts and human health, ecological balance, and economic growth. It also reduces the reliability and applicability of those studies which have been done. Last but not least, the quantitative assessment of environment risks of geothermal energy development involves multiple disciplines, and researchers who have sufficient background in environment, geology, health, ecology, and economics are rare.

4.2 Comprehensive assessment framework

Existing studies have started to pay attention to evaluating losses to society and the public induced by geothermal environmental risks. Specifically, a large variety of physics-based models have been established to predict damage due to geological hazards in geothermal fields and statistical models have been built to assess health or economic losses. However, a comprehensive approach for evaluating social, ecological, and economic losses caused by adverse environmental impacts of geothermal energy has not been developed yet.

Currently, some international institutes such as the International Atomic Energy Agency and the Gold Standard Foundation, have established indicator-based sustainable development assessment frameworks for energy. These could provide a reference for assessing the environmental risks of geothermal development. In the process of setting up the indicator assessment system, the selection and application of indicators would be of crucial importance to the efficacy of the assessment. The weight of indicators varies from national conditions, regional geological setting, and project-specific features. Therefore, well-rounded investigations and consultations will be required to select appropriate indicators and determine how to apply them. Moreover, to increase data

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collection capabilities and improve the range and quality of these data, governments should establish organizations individually responsible for collecting each type of data, as well as build an interactive platform for data sharing.

An indicator-based assessment framework is necessary to evaluate the real impacts of geothermal energy development and the current status of the geothermal system. Nevertheless, this is insufficient for governments and investors to make decisions because it is more important for them to understand impacts of geothermal development on the living environment of future generations. It is therefore essential to introduce other methods into the comprehensive assessment framework for the environmental impacts of geothermal development. Here, we propose a preliminarily comprehensive assessment framework that combines these indicators with the methodologies reviewed in this study.

Fig. 8 is an outline of a comprehensive assessment framework for the environment risks of geothermal development. The proposed assessment framework consists of five modules, namely database, physics-based models, statistical models, multi-indicator assessment framework, and traffic light system. The components and functions of these modules are as follows:

- Database: This contains raw data related to such factors as resource potential, geological setting, regional population and economy, groundwater composition, biological components, types of buildings, and geothermal projects practices and operations. Notably, most of the data are time series.

- Physics-based models: These are mainly used to predict the occurrence rate and intensity of seismic activities induced by geothermal development and use. The examples of existing physics-based models are given in Section 3.1.
- Statistical models: These have two primary functions. One is to explore the losses caused by geothermal environmental impacts, such as an increase in medical expenses. The other is to predict the development trend of indicators under different scenarios, such as future changes in vegetation coverage.
- Multi-indicator assessment framework: This is classified into four dimensions: geological hazards, human health, ecological system, and economic development. These classifications can be further subdivided, depending on the specific situation. Note that some indicators can occur more than once, given the numerous interlinkages among these categories.
- Traffic light system: Three levels are defined, including red, amber, and green. Also, the meaning of each level is similar to the traffic light rule, with the red representing high risk (to stop), the amber indicating medium risk (to be cautious), while the green representing low risk (to

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proceed). What is more, the lower and upper limits of each risk level are different from project to project, given the unique circumstances for each geothermal project. Therefore, it is of great importance to conduct extensive consultation before setting the limits of each risk level.

Also, there exist complicated relationships between these modules, which are represented by lines A-G. The interpretations of these lines are given by the following:

- Line A & B: Data is imported to specific models.
- Line C: Past and present values of indicators are directly extracted to the multi-indicator assessment framework in order to assess the risks already created by geothermal use and the current status of the geothermal system.
- Line D & E: The future impacts and risks of geothermal development are predicted and evaluated based on the estimated future indicators.
- Line F & G: Risk assessment is conducted based on a single indicator, to consider the extreme value and the environmental impacts of geothermal use from one perspective.
- Line H: Risk assessment is made based on a comprehensive indicator, with the consideration of the all-round impacts of geothermal use.

Certainly, there are also other relationships. For example, the correlations between parameters of physics-based models are captured by statistical models. In this study, our focus has been on the most critical relationships. Hence other links are not indicated.

Assessment processes vary with geothermal technologies or projects, not all modules suitable for all geothermal projects. For example, for shallow geothermal energy systems, they have little or no impact on geological subsidence and induced seismicity, so there is no need to predict the occurrence of seismic hazards. Therefore, further work is needed to distinguish assessments of environmental risks of main technologies, such as ground source energy technologies, thermal energy storage, and EGS.

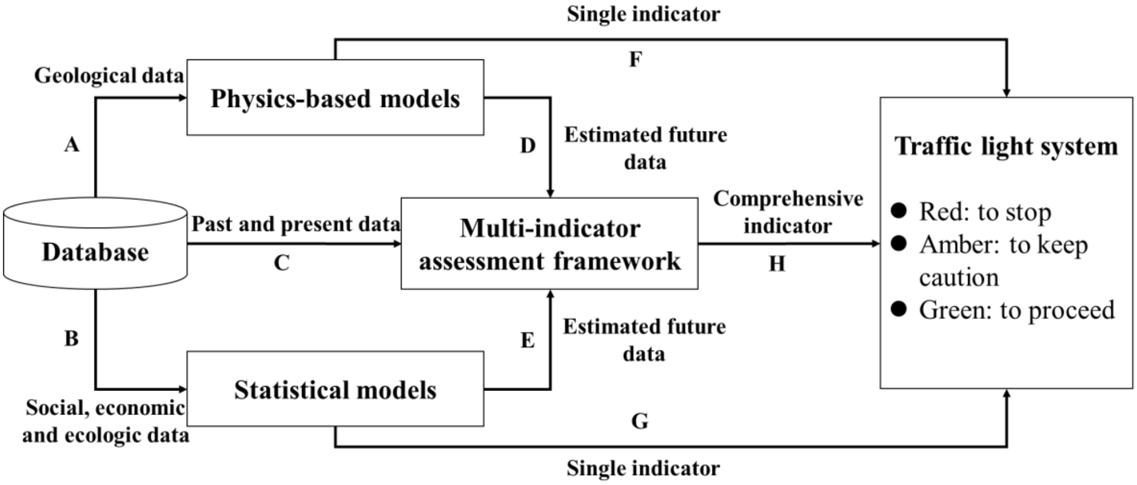

Fig. 8 Comprehensive assessment framework for environment risks of geothermal energy development

5. Conclusions

The present review has shown a diverse range of environmental risks resulting from geothermal energy development. These risks may further cause adverse consequences on human health, the ecological system, and the local economy. Despite a rising consciousness about potential adverse environmental impacts of geothermal energy development, clear definitions and quantifications of these environmental impacts and their

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ramifications have not been developed.

There exist factors that constrain the formation and application of quantitative assessment methodologies for geothermal environmental risks. Firstly, each geothermal project has its own inherent uniqueness, which is not conducive to the model generalization. Secondly, some effects of geothermal environment impacts on human health, ecological system and the economy have a long incubation period, therefore they are hard to measure and quantify. Thirdly, the boundary and value of potentially threatened environments are difficult to define and estimate. Fourthly, relevant data and details of geothermal projects are limited. Last but not least, the quantitative assessment for environmental risks of geothermal energy development involves multiple disciplines, which requests higher quality and ability on researchers.

To fill the gap in the literature, this study summarizes the geothermal geological hazards and pollutions and their main quantitative methods as well as analytical frameworks. There are various existing models based on different datasets for forecasting the intensity of geological hazards, and assessing the environment risks of geothermal energy from the human health, ecological system, and economy respectively. In the present study, a comprehensive framework for assessing environment risks of geothermal energy from various aspects has been proposed. For the sake of higher accuracy and reliability of the proposed framework, it is advised to establish a geothermal data-sharing platform, and multi-disciplinary modeling need to be focused in the future work.

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