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Developing and enforcing fracking regulations to protect groundwater resources

S. Esterhuyse[1]✉, D. Vermeulen[2] and J. Glazewski[3]

Unconventional oil and gas (UOG) extraction can augment energy supplies in countries with viable gas resources, but it risks damaging water resources. Water supply problems for fracking can also limit UOG extraction, especially in water-stressed regions. Regulations are one of the main tools used to minimize UOG extraction impacts on water resources. Many states in the US and Canada have extensive regulations to protect water resources during UOG extraction but they are often ineffective, either because they were poorly drafted or because they are not properly enforced. South Africa is a water-scarce, groundwater-dependent country that is considering UOG extraction in the future. South African groundwater experts were surveyed on what regulations are needed to protect groundwater resources and how to enforce them. This study recommends specific UOG extraction regulations to protect groundwater resources, which are not only relevant to South Africa, but also to other countries that extract UOG resources.

npj Clean Water (2022)5:3 ; https://doi.org/10.1038/s41545-021-00145-y

INTRODUCTION

Unconventional oil and gas (UOG) extraction using hydraulic fracturing (fracking) in shale areas could alleviate country energy shortages. Fracking however poses serious environmental risks, particularly to water resources[1–8]. Problems in obtaining water for fracking are also curtailing the development of UOG industries, especially in water-stressed regions[9,10]. About 31% of shale areas worldwide are water-stressed, defined as areas where human consumptive water demand already exceeds the availability of local renewable 'blue water' (surface water and groundwater)[10]. Depending on the expansion of UOG extraction, as much as 44% of future UOG extraction areas could be water-stressed. Current water-stressed areas include the south-central United States, Canada, Argentina, South Africa, North Africa, China, India, and Australia[10]. In such regions, fracking could use more than 50% of the regional water resources during complete UOG extraction, which could aggravate competition for water, or even place unsustainable pressure on the water resources[10].

Regulations are vital for minimizing damage to water resources during UOG extraction. Many states in the US and Canada, where UOG resources have been extracted the longest, have extensive regulations to protect water resources. These regulations are however often a patchwork—with some being specific and prescriptive, and others vague and general[11,12]. It is, therefore, crucial to develop and enforce suitable regulations to protect water resources.

Our in-depth study assessed different UOG extraction regulations for South Africa, a seriously water-constrained, groundwater-dependent country that is considering UOG extraction in the future. We also assessed how such regulations could be effectively enforced. The recommendations from this study could also be useful to other countries where UOG resources are being extracted.

South Africa—a water-stressed country planning to extract UOG resources

South Africa relies on coal for 90% of its electricity needs[13]. These coal resources are being depleted and South Africa is in dire need of additional energy, having suffered rolling blackouts since 2008[14]. Extracting UOG resources in South Africa's Karoo Basin is one of the options being considered. While the continued extraction of fossil fuels such as coal, or indeed UOG, is questionable given the state of climate change[15], UOG may serve as a transition fuel to cleaner energy[16,17]. South Africa is however water-scarce, as illustrated by the 2016–2018 Cape Town drought crisis[18]. Figure 1 shows relevant water-related features and studies that were done in the Karoo Basin. A 2016 strategic environmental assessment (SEA) on shale gas extraction in the Karoo basin shale gas target area, identified water supply for fracking as one of the main factors limiting the UOG industry's development[19]. A regional baseline groundwater monitoring network, recommended by the SEA, is currently being developed for this area.

Communities in the Karoo Basin, with its very low annual rainfall and limited perennial rivers, depend heavily on groundwater. The Karoo basin's dolerite dykes and sills, which cover most of the basin, are its main water provisioning features, but can also act as pollution pathways for contaminants that infiltrate from the surface and that may migrate from deep to shallow aquifers during UOG extraction[19]. Saline artesian aquifers, postulated to occur in the southern part of the Karoo, where artesian flows have been encountered in deep Soekor wells at depths exceeding 4000 m[19], also present a contamination risk. These regional artesian aquifer conditions occur south of the southern limit of the dolerite intrusions, with the Great Escarpment marking the northern limit of this deep artesian flow. Rocks of the Cape Supergroup that underlies the area south of the Great Escarpment are under sufficient hydrostatic and lithostatic pressure to allow deep groundwater to reach the surface. The Karoo's groundwater is vital for agriculture and for household use, so the specific vulnerabilities of the Karoo aquifers are a matter of concern[20,21].

Fracking is contentious in South Africa and has been met with public resistance[22,23]. The first permit applications for UOG extraction in South Africa were submitted in 2011, yet proper regulations to protect water resources must still be drafted. The only fracking-specific regulations released by the South African

[1]Centre for Environmental Management, University of the Free State, Bloemfontein, South Africa. [2]Institute for Groundwater Studies, University of the Free State, Bloemfontein, South Africa. [3]Institute for Marine and Environmental Law, University of Cape Town, Cape Town, South Africa. ✉email: esterhuyses@ufs.ac.za

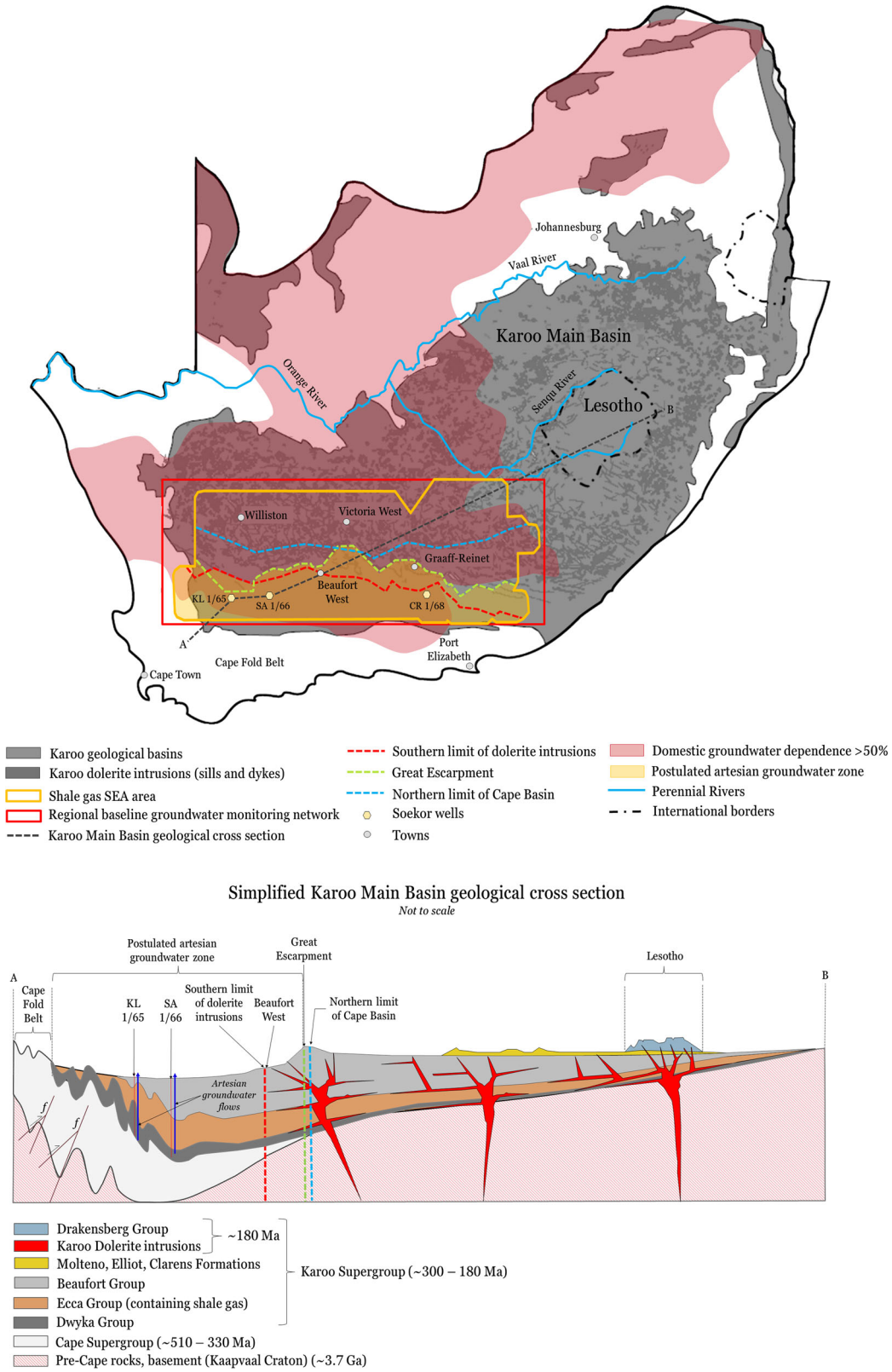

Fig. 1 Water-related features of South Africa's Karoo Basin. Plan view map showing South Africa's Karoo Basin, important study areas (the shale gas SEA study area and the Regional baseline groundwater monitoring network), important geological features (the Karoo dolerite intrusions, the Southern limit of the dolerite intrusions and the Northern limit of the Cape Basin), and important topographical features (the Great Escarpment). The map also shows areas of high domestic groundwater dependence (covering most of the Karoo Basin shale gas target area) and the postulated artesian groundwater zone within the shale gas SEA study area. A simplified geological cross-section (A-B) of the Karoo Main Basin is presented below the map.

Department of Mineral Resources (DMR) in 2015, were challenged in court. They were invalidated in 2019 by the South African Supreme Court of Appeal, because the DMR did not have the mandate to draft water regulations[24], and because they failed to sufficiently protect water resources[21,22,24].

RESULTS

Regulations to protect groundwater during UOG extraction

We asked 20 South African groundwater experts their opinions on the importance and enforceability of regulations that we proposed for protecting groundwater resources during UOG extraction. We grouped the regulations according to eight regulatory areas: baseline monitoring, management plans, margin of safety regulations, prohibitory precautionary regulations, monitoring and reporting of resources and processes, best applicable technologies and processes, public information disclosure, and well decommissioning. These are discussed below (see Fig. 2). The supplementary materials provide detailed information on responses per regulatory area (Supplementary Figs. 1 to 8). Additional regulatory suggestions made by respondents can be seen in Supplementary Table 1.

Baseline monitoring. provides water resource information before oil and gas extraction starts and must consider the appropriate density of monitoring points, frequency of monitoring, and time periods[25,26]. Baseline water use data protects existing water uses during water resources allocation for extraction, while baseline water quality information alert regulators to contamination events and can be used to determine rehabilitation targets[27]. Baselines are indispensable for establishing a legal basis for proving contamination, identifying the party responsible for the contamination, or for a company to refute a contamination claim[12]. All respondents viewed the monitoring of groundwater quality, groundwater availability for fracking, and baseline mapping of geological structures as important. Most respondents viewed seismicity mapping, earthquake zone mapping, and the prediction of future seismicity linked to underground wastewater injection (UWI) (if allowed by South Africa) as important. The monitoring of baseline groundwater quality, groundwater availability for fracking, and baseline mapping of geological structures were viewed as the easiest regulations to enforce, and seismicity mapping as the most difficult. Four respondents doubted whether the South African regulator can enforce baseline monitoring regulations, because of insufficient funding, lack of expertise, weak institutions, absence of legislation and regulations, lack of political will, and corruption.

Management plans. are common command-and-control regulatory tools to obtain data on the fracking process[25,26,28,29]. All respondents considered it important to have plans for waste management, well decommissioning, and specification of water sources for fracking in place before proceeding with UOG extraction. Most respondents considered a drilling management plan and a hydraulic fracturing management plan important for minimizing damage to groundwater, but only 60% thought a hydraulic fracturing management plan to minimize seismic activity was important. One respondent stated that drilling contractors' protocols should be reviewed under a protocol management plan, while 10% of respondents supported the review of management plans by an independent transparent expert panel and its implementation in consultation with all relevant stakeholders. Only the waste management plan and the plan specifying sources of water for fracking was considered relatively easy to enforce. According to 20% of respondents, a shortage of government human resources and financial capacity would hamper enforcement in South Africa.

Margin of safety regulations. intend to limit groundwater contamination and ensure proper groundwater use during UOG extraction. They commonly specify well spacing and density, water quality discharge standards, environmental critical level limits, and discharge volume limits[30]. Minimum distances (setbacks) can also be specified between fracking operations and sensitive geological structures, aquifers, and earthquake-prone areas[25,26]. All respondents viewed regulations for limiting negative groundwater impacts from waste or wastewater as important. Waste-related margin of safety regulations included wastewater release discharge standards and setback distances between waste management operations and sensitive aquifers, aquifer recharge areas, and geological structures. Only 60% of respondents viewed the regulation of well spacing density as important Well spacing density regulations and wastewater release discharge standards were considered as the easiest to enforce, and setbacks between waste management operations and aquifer recharge areas and between production wells and geological structures as the most difficult. Regulations on minimum setback distances between fracking wells and ancillary activities and groundwater features were also assessed, specifically for South African groundwater conditions (see Supplementary Table 2). Respondents had to indicate whether they agreed with the proposed minimum setback distances. Alternative setback distances or protection approaches could be proposed where respondents did not agree with the minimum setback distances. Most respondents proposed much more stringent setbacks, for example between town water supply and production wells. Respondents proposed a minimum setback distance of 10 km both between town water supply boreholes and UOG production wells and between towns and any future production wells. Groundwater is very important in South Africa[31]. An estimated 45.5% of the country's surface area is more than 50% dependent on groundwater supply for domestic needs[32]. Twenty percent of respondents stated that setbacks should be calculated on a risk-based case-by-case basis according to local geological and hydrogeological conditions at each site, allowing for more lenient setbacks, but also a tougher approach in high-risk cases. The setbacks that we tested were all horizontal distances. One respondent, however, proposed a vertical restriction for fracking in South Africa specifically—no fracking in target shale formations less than 1000 m deep, and that fracking only be allowed in shale formations less than 1500 m deep, if a comprehensive hydrogeological conceptual model has been developed.

Prohibitory precautionary regulations. prohibit UOG operators from executing certain activities during UOG extraction, to protect groundwater resources[29,33]. Respondents viewed prohibiting the use of harmful, toxic, or carcinogenic chemicals as the most important regulation, but one that is difficult to enforce. Here regulators could follow the precautionary approach and require companies to prove the safety of their chemicals before use[30,34], ensuring more transparency in the fracking industry and encouraging the development of safe fracking chemicals[35,36]. Prohibiting UWI and fracking in sensitive aquifers were also viewed as very important. Even though UWI is commonly practiced in the US[37], UWI is a particular concern in South Africa because the country relies on groundwater and because possible shallow-deep aquifer connectivity can cause fracking fluid and contaminant migration to freshwater aquifers.

Monitoring and reporting of resources, processes, and incidents. intend to ensure aquifer integrity and protect groundwater quality and quantity[35]. All respondents considered monitoring and reporting of resources and processes as very important, with one considering it 'probably *the* most important aspect' of UOG extraction. Monitoring of waste generation and waste management, groundwater quality and quantity impacts during and after

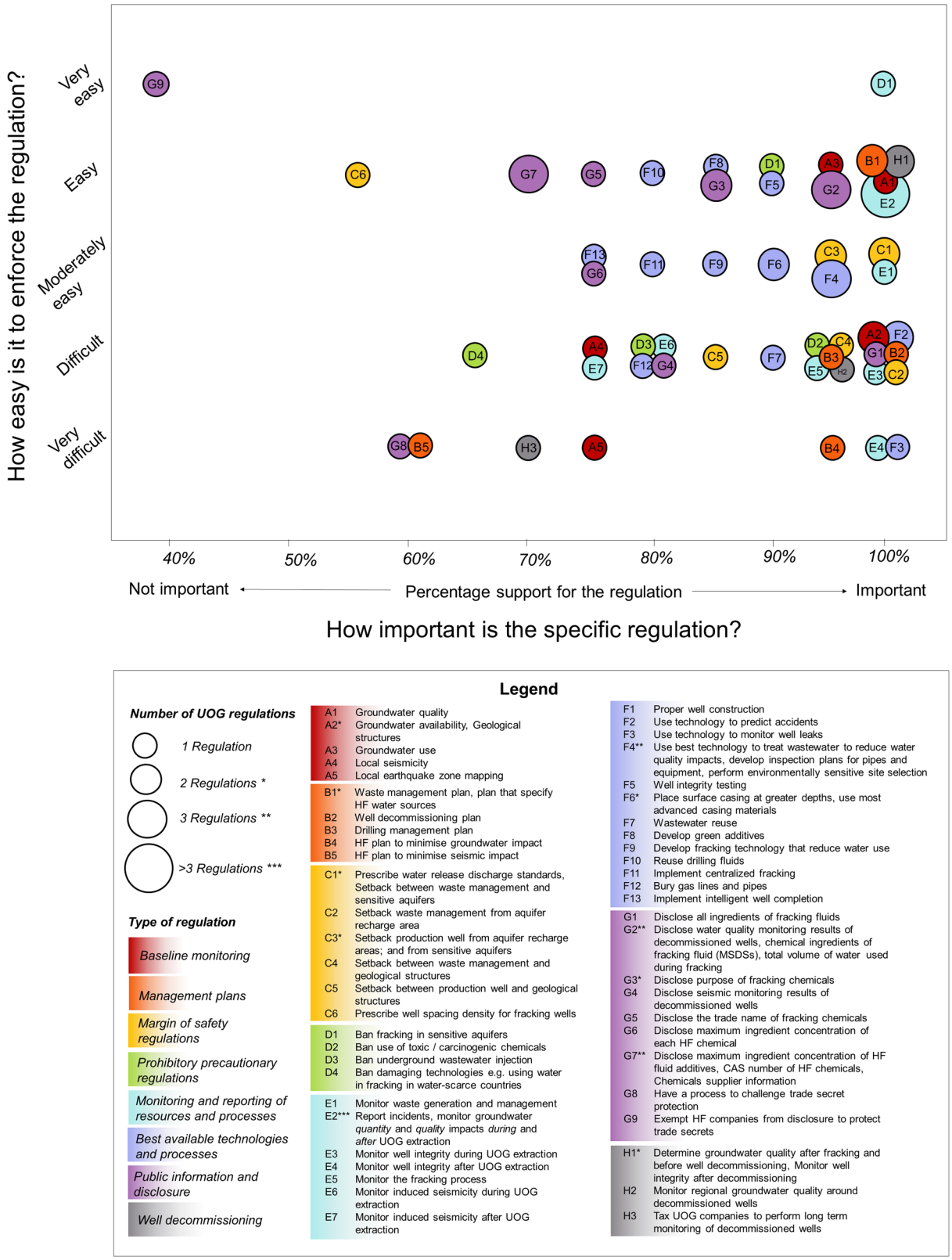

Fig. 2 Importance and ease of enforcement of proposed groundwater regulations ($n = 20$). Percentage of respondents viewing specific UOG extraction regulations for protecting groundwater resources as important and how easy respondents think their enforcement would be.

UOG extraction, the fracking process, well integrity during and after UOG extraction, induced seismicity, and reporting any incidents were all considered important. Of all the monitoring regulations, well integrity was viewed as most difficult to enforce, especially after well decommissioning, probably because of the lack of clear well-decommissioning guidelines. Respondents also viewed the establishment of an independent UOG extraction monitoring committee to implement regional monitoring and audit the operators' site-specific monitoring protocols as important. Such compliance monitoring and enforcement could provide credibility and ensure effective governance.

Best available technologies and practices (BATP). is a precautionary regulation that demands the use of such technologies and practices to avoid harm to water resources[38]. Most respondents viewed the proposed BATP regulations as very important, as underscored by the position statement by South Africa's Centre for Environmental Rights[39]. The BATP regulations that respondents viewed as most important were proper well construction and using technologies to predict, prevent and mitigate accidents and monitor for well leakages. According to one respondent, technologies should not be prescribed by the regulator but left to the operator (i.e. the regulations should set the goalposts but allow the industry the space to meet the objectives taking a risk-based approach), as the regulator is generally not sufficiently experienced to identify best practices and the industry is in a better position to innovate and introduce fit-for-purpose applications. Another respondent, however, said BATP must be defined for each operational step and that operators and regulators must have a common understanding of BATP, since one operator's BATP may be better than another's.

Public information and disclosure (PID). regulations facilitate public disclosure and the independent review of testing procedures and results[29,35]. Respondents viewed these regulations as important, with the most important being the disclosure of all ingredients in fracking fluids, followed by water quality monitoring results from decommissioned wells and the total volume of water used in fracking. Only 40% of respondents thought fracking companies should be exempted from disclosure, to protect trade secrets, and 60% approved of a process to challenge trade secret protection, to stop companies from obtaining an exemption from certain disclosures. Three respondents took serious issue with trade secret exemptions. One of them said there should be '*no* exceptions to disclosing information and that 'trade secrets' were not a valid excuse and therefore saw no need for a process to challenge a claim for a 'trade secret'. Respondents considered the disclosure of fracking fluids and the trade name of fracking chemicals and suppliers the most difficult to enforce. Respondents suggested improvements to disclosures, including ensuring the responsible use of publicly disclosed information (to minimize misuse of information by campaign groups), ensuring that operators can be trusted to produce truthful disclosure reports of chemicals used in *each* well, as these can differ, having public input into the licensing process and having a disclosure format that can be understood by a layperson.

Well decommissioning regulations. aim to protect groundwater over the long term. Between 1.9 and 75% of oil and gas wells fail due to mechanical well casing failure[5], and could contaminate groundwater. The safe decommissioning and continued monitoring of decommissioned wells are therefore paramount to protect groundwater quality over the long term[5,40]. Respondents were unanimous that a groundwater quality survey before fracking is indispensable to serve as a baseline after well decommissioning. Well integrity monitoring after well decommissioning, monitoring groundwater quality in the vicinity of decommissioned wells, and taxes for long-term monitoring after decommissioning were also viewed as important. Respondents viewed monitoring well integrity after closure and imposing taxes to ensure long-term monitoring as the most difficult regulations to enforce.

South Africa's capacity to enforce UOG extraction and fracking regulations

Regulations must be properly enforced to ensure water resources protection. To ensure compliance with and enforcement of UOG regulations, respondents felt that fining UOG operators who did not comply was an important tool to ensure compliance with regulations. Another would be requiring them to compensate for pollution incidents, for example by supplying water where water sources are polluted. One respondent did not believe operators would do this if pollution only surfaced 5–10 years after they had left a fracking area, and proposed that operators be levied during their operations for remedying future pollution incidents and that such funds be separately managed by an institution independent from government. Supplying financial security in terms of obligations related to water use licenses and for addressing latent and residual water-related impacts arising from UOG extraction was also viewed as very important. One respondent felt that personal liability should also be considered as a deterrent for activities that may cause groundwater pollution.

To ensure compliance with regulations, enforcement mechanisms must be implemented by government. We, therefore, assessed South Africa's policies and institutional capacity to enforce regulations on UOG extraction and fracking. We compared our 2019 capacity survey results with those of a 2012 survey, in which we asked different respondents from the same institutions the same questions[41]. Institutional capacity constraints are, according to the respondents, 'the crux of the shale gas development issue in South Africa' and 'our biggest challenge', and they fear that UOG extraction 'will completely over-extend the already very limited capacity within our government departments'.

All but one respondent felt that South Africa does not have the institutional capacity to enforce compliance with specified license conditions or to monitor UOG extraction operations. Ninety percent of respondents also felt strongly that fragmented departmental responsibilities and conflicting departmental mandates would make it complicated to regulate UOG extraction[22]. Eighty percent of respondents felt that the Mineral and Petroleum Resources Development Act of 2002, the main Act regulating oil and gas extraction, is insufficient in scope to handle fracking and that amendments would be required to our statutes. Sixty-five percent stated that South Africa does not have specific policies to deal with fracking or sufficient regulations to control it. As mentioned earlier, South Africa's only fracking-specific regulations, drafted in 2015, were set aside in court because they did not sufficiently protect groundwater resources[21,22].

To enforce regulations, 90% of respondents agreed that fracking-specific legislation and regulations must be developed, and particularly monitoring protocols. Sixty-five percent of respondents felt that self-regulation and reporting to government could alleviate government human resource pressures and that market-based regulatory tools would also be useful in addition to command-and-control regulations such as margin-of-safety regulations or BATP. Our respondents supported strong measures to ensure compliance, such as an independent regulatory entity reporting to government, a central database, and fines for violators. It is important, however, to note that 70% of them said a SEA on available energy generation options must be done before South Africa decides whether to allow UOG extraction. Finally, when asked whether South Africa can protect groundwater resources effectively by regulating UOG extraction, only 30% of respondents believed this would be possible.

DISCUSSION

The South African government actively supports UOG development to augment its energy supplies[23]. To develop a UOG extraction regulatory framework, South Africa has published fracking regulations in 2015 and commissioned a shale gas development SEA in 2016. The 2015 fracking regulations have however been invalidated. The South African government can currently not permit UOG extraction due to the lack of a clear regulatory framework to protect water resources during fracking. Water sourcing for fracking in water-scarce South Africa is a serious regulatory concern and is viewed as the main factor limiting UOG development in South Africa[19], similar to China[42,43]. Internationally, regulations to protect groundwater from contamination during UOG extraction are also extremely important, both for water-scarce and water-abundant countries[1–4,44]. The US has extensive regulations to protect groundwater resources[12], but despite the importance of protecting groundwater, some US states still fail at regulating UOG extraction[12], frustrating efforts to identify water resource contamination and determine liability[45]. Given the risks to water resources, and considering the precautionary principle, regulations to properly protect South African groundwater resources must be drafted.

To assist in the development of a UOG extraction regulatory framework to protect South African groundwater resources, we assessed the usefulness and enforceability of specific regulations. Of these, baselines of water use and water quality before fracking are indispensable for protecting groundwater resources. Respondents doubted whether the South African regulator can enforce baseline monitoring regulations and called for a sophisticated regulator with state-of-the-art monitoring equipment and systems, integrity, and codes of ethics, an ability to operate independently, and competent staff empowered to enforce regulations, such as shutting down an expensive drilling operation when there are real safety concerns. Internationally, the lack of baselines before fracking challenges the identification of groundwater contamination sources and extents[46–48]. Under margin of safety regulations, regulating well spacing density, although not viewed as very important by most respondents, could also ensure a smaller surface footprint and limit wastewater generation[49]. A lower density of surface wells would also limit possible interaction between hydraulically generated fractures and existing wells or other underground infrastructure[50], thereby limiting upward migration of contaminants into freshwater aquifers. Under margin of safety regulations, the enforcement of setbacks for aquifer recharge areas and geological structures were viewed as the most difficult to enforce, because geological and hydrogeological complexity complicates the identification of all the sensitive aquifers and geological structures that could be at risk[19]. Groundwater characterization data in South Africa (and sub-Saharan Africa) is limited because of continued underinvestment in groundwater, while technical and institutional capacity constraints hamper sustainable groundwater development and management[51–53]. Limited groundwater data is also an international concern[7]. In South Africa, an important margin-of-safety regulation is the setting of a vertical limit for fracking at 1500 m below surface. Karoo hot springs indicate geothermal circulation at 700–800 m below surface, making a connection between deep and shallow aquifers more likely at depths of less than 1500 m. Recent research indicates some degree of connection between the Beaufort and the gas-containing Ecca aquifers, legitimizing concerns about shallow-deep aquifer connections[54,55]. Internationally, prohibitory precautionary regulations to protect water resources are difficult to enforce because of UOG operator pushback against such prohibitions, which abounds in countries that use fracking[56]. Respondents viewed prohibiting the use of harmful, toxic, or carcinogenic chemicals as the most important prohibitory regulation, but also the most difficult to enforce, possibly because it would be difficult to independently determine if UOG operators are using prohibited chemicals. BATP regulations reduce pollution but often suffer from underinvestment[57]. Its effective implementation is hampered by a time lag between technological development in the UOG industry and government adaptation of regulations to include the most recent BATP. Governments could incentivize BATP adoption by giving tax breaks to companies that develop better BATP. PID regulations, such as disclosing fracking chemicals, even though extremely important for groundwater protection, are often difficult to enforce because of the desire to protect trade secrets[56]. Governments could exempt fracking companies from publicly disclosing information to protect trade secrets, and have a process to challenge trade secret protection, to stop companies from obtaining an exemption from certain disclosures. Most South African respondents did however not favor this option. Companies often actively undermine disclosure policies by lobbying for weaker regulations, or 'drown' users in disclosure information, sometimes in such a format that information users do not have the time, resources, or expertise to analyse it effectively[58,59]. All respondents viewed PID regulations as difficult to enforce and usable information hard to obtain. Proper well decommissioning is important to avoid legacy groundwater contamination issues[12]. Enforcing well integrity monitoring after closure and imposing taxes to ensure long-term monitoring can however be difficult because it is difficult to determine how to decommission a well safely yet still be able to monitor it. In South Africa, collecting and administering taxes for long-term monitoring may also be problematic, given the current poor governance of our natural resources, with corruption and bribes, real and reputed, abounding[22]. Further, South Africa taxes go into the general fiscus and there is no mechanism to ensure that the money will be used for long-term monitoring or legacy impacts.

Poor enforcement is where even the best regulations could fail. Only a third of the respondents felt that South Africa would be able to protect groundwater resources properly by regulating UOG extraction, not because the regulations themselves would be technically challenging to comply with, but because regulators, not only in South Africa but also internationally, do not know enough about the risks of UOG development to draft proper regulations[44,60–62]. Other reasons include that regulation is complex because of the fragmented departmental responsibilities and conflicting departmental mandates (a problem also observed in the US, Canada and China[36,63,64]. In South Africa, institutional capacity is also insufficient to monitor fracking activities and UOG extraction impacts on natural resources (a problem also observed in the US, Canada, and China[7,42,65–67]). For example, more than half the oil and gas wells in the US are not inspected annually to check compliance with regulations and some state agencies cannot employ enough employees for their oversight programmes, with the result that violators are less likely to be cited, fined, or prosecuted[34,68]. Lastly, the political will to enforce compliance with UOG extraction regulations lacks, not only in South Africa and other developing countries (China, Argentina, and Brazil)[42,69,70] but also in developed countries such as Spain and the US[34,68,71–73]. Financial securities can be used to enforce regulations. Operators should not view a financial security requirement or the levying of impact funds as a license to pollute. In the US, discretionary review, tiered monetary penalties, and civil suits are common enforcement mechanisms[74]. As these do not, however, provide sufficient compliance incentives or penalties for non-compliance, enforcement could benefit from the additional tool of criminal sanctions for significant violations, if applied fairly (in proportion to the violation[74].

Self-regulation and reporting to government, as well as market-based regulatory tools, could alleviate government capacity pressures and ensure better enforcement of regulations in countries not properly equipped to regulate UOG extraction.

In countries with regulatory capacity constraints and corruption concerns, the establishment of an independent regulatory entity with a scientific background in fracking could help governments by drafting and regularly reviewing regulations tailored to the country's specific needs. Here, country-specific geological complexities, governance structures, capacity constraints, and technological advances should be considered. It could also establish and administer an independent trust fund to manage collected funds for long-term monitoring after well decommissioning and perform regional monitoring of groundwater resources in UOG extraction areas and reporting to government. Lastly, it could perform compliance monitoring of UOG extraction operations and store all data in a publicly accessible central database, and ensuring proper dissemination of data to all interested and affected parties. Such an entity would have to be transparent and have the trust of the regulators, the operators, and the general public. It would have to be comprised of stakeholders from all three groups. All data gathered by such an entity would have to be stored in a publicly accessible central database, which could be used for studies and to assess compliance with regulations. Access to UOG extraction and monitoring data would be paramount to ensure proper enforcement of regulations. Without good governance and proper enforcement, any regulations to protect groundwater resources would fail dismally.

An important issue highlighted by the survey was that two-thirds of the South African respondents felt that the government must do a SEA of available energy generation options, *before* deciding whether to allow UOG extraction. This is important because water resources are the one main limiting factor for UOG extraction in water-scarce countries. First performing such an assessment, prioritising energy generation options, and then drafting regulations for UOG extraction (if it is seen as a viable option), would uphold the South African constitutional obligation to promote sustainable development and pass reasonable legislative (and other) measures to protect the environment 'for the benefit of present and future generations'.

This study offers crucial insights into how to protect groundwater resources during UOG extraction, using regulations. Fracking can use a large amount of groundwater and also pollute groundwater resources, a major concern in many water-scarce countries. It is therefore important that governments protect groundwater resources during UOG extraction, especially when considering additional stressors such as population growth or climate change. Many studies have looked at specific regulations to protect water resources during UOG extraction. We have gone further: we reviewed, classified, and systematically tested the many different regulations that are currently applied internationally (sometimes in a patchwork fashion), to assess their usefulness in protecting groundwater resources.

Our survey of expert responses was done in South Africa and some of our proposed UOG extraction regulations are specific to South Africa's geography and governance systems. Nevertheless, most of the insights this paper offers would be useful for any country that must still develop regulations, or whose current regulations need amendment.

METHODS

Survey design

We canvassed 20 respondents' opinions on the importance and enforceability of UOG extraction regulations we proposed that were designed to protect groundwater resources during all the phases of extraction, from before exploration until after well decommissioning.

Our regulations, classified into eight groups (Fig. 2), were based on a detailed examination of UOG extraction regulations commonly used to protect groundwater resources in countries that have such regulations in place, and a long history of UOG extraction: the US, Canada Australia, and the UK[12]. We also assessed respondents' views on the capacity of the South African government to enforce these regulations successfully, via a list of carefully structured questions on South Africa's fracking policy, governance structure, and current legislation and regulations that are in place.

We designed a self-administered structured questionnaire to test the respondents' perceptions and opinions of our proposed fracking regulations, as this is a good tool to elicit stakeholder opinions at a pre-decision phase[75]. In South Africa, previous drafts of fracking regulations had been rejected, so we are still in the pre-decision phase of the drafting of fracking regulations. The self-administered questionnaire also allowed informants time to complete the survey on their own schedules, with additional time to collect information to help inform their responses and ensure carefully considered responses[76]. The questionnaire gave respondents considerable flexibility by including open-ended questions where they could describe their reasoning or any other concerns not captured in the Likert scale questions. Our survey was anonymous to increase our chances of eliciting stakeholder opinions, as fracking is a sensitive and contentious topic in South Africa[77]. Anonymity meant that the respondents could give their considered opinions unconstrained by corporate, political, or other considerations[78,79].

Eliciting viewpoints from knowledgeable informants, referred to in the literature as 'key informant elicitation', can make a valuable contribution to informed decision-making and is a useful tool to explore regulatory uncertainty (in this case UOG extraction regulation). To obtain carefully considered and meaningful judgments based on a systematic consideration of all relevant evidence, we took the question on UOG regulation apart into its component pieces so we could ask respondents to rate the importance and enforceability of a very detailed and specific list of regulations. This gave us eight regulatory areas:

- Baseline monitoring
- Management plans
- Margin of safety regulations
- Prohibitory precautionary regulations
- Monitoring and reporting of resources and processes
- Best available technologies and processes (BATP)
- Public information and disclosure
- Well decommissioning

The questionnaire was carefully developed over several months. We tested it on two groundwater practitioners with knowledge of fracking in countries outside South Africa. Two respondents with no groundwater knowledge, but with fracking knowledge, also read it to determine whether the questionnaire was generally understandable. Feedback gathered this way was incorporated into the questionnaire. We did not test the questionnaire on any of our targeted respondents (South African groundwater specialists) to ensure that we did not unduly influence them during the development phase of the questionnaire. We also took care to ensure that any possibly unfamiliar concepts were explained in our questionnaire, to ensure that respondents understood the questions and could give proper feedback.

We emailed our respondents the survey, gave them time to go through the questionnaire, and then contacted them to discuss any uncertainties they might have about any of the questions. Respondents could also contact us with any questions or concerns while completing the questionnaire, or afterwards if they wanted to add more information to any open-ended questions. The survey was launched in November 2018 and closed in August 2019.

Respondents

Successful eliciting of information from respondents depends on the respondents' knowledge and commitment. Given our focus on *regulations to protect groundwater resources during UOG extraction*, our ideal respondents were groundwater specialists with knowledge of UOG extraction and fracking through work or research. Because our target group was very specific, our sample was of necessity small. We used publication history and peer nomination of groundwater specialists to select our respondents. We approached 31 South African groundwater specialists, which represented the whole pool of suitable respondents. Twenty of these completed the survey, a response rate of 64.5%. Some potential respondents declined to complete the survey due to the sensitive nature of this subject in South Africa, or because they felt that they did not know enough about the subject. Sixty-five percent of respondents ($n = 13$) had more than 10 years' groundwater experience, and of those, 69% ($n = 9$) had more than 20 years' experience.

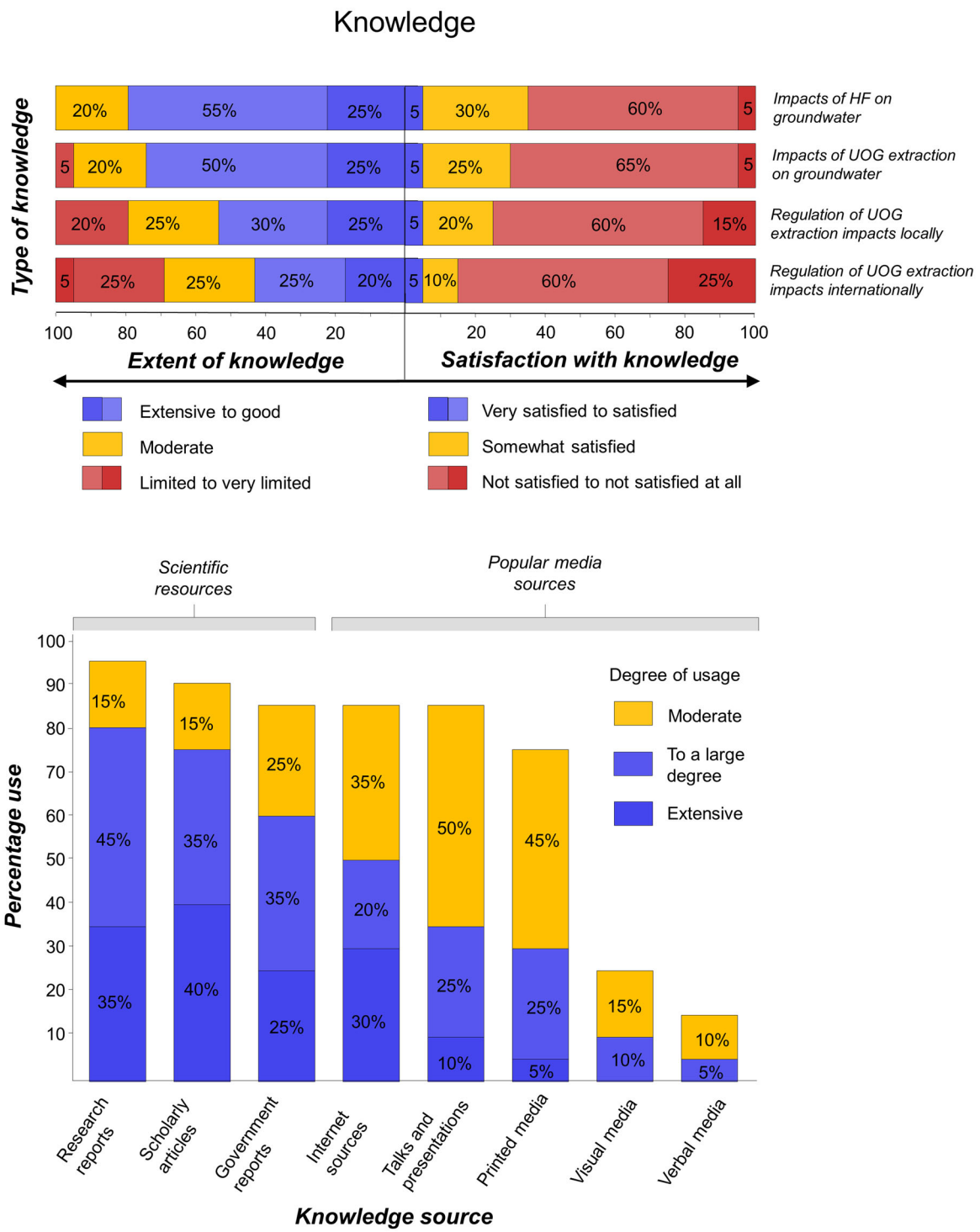

Fig. 3 Extent of knowledge, satisfaction with knowledge and knowledge sources (n = 20). Extent of respondents' knowledge on the impacts of hydraulic fracturing (HF) and unconventional oil and gas (UOG) extraction, knowledge on the regulation of UOG extraction, satisfaction with this knowledge, and the extent to which different knowledge sources have been consulted by the respondents.

To assess their knowledge levels, we asked them to rate the extent of their knowledge about UOG extraction and fracking, their levels of satisfaction with their knowledge, and to indicate the sources of their knowledge (Fig. 3). Most felt that their knowledge about groundwater impacts from both fracking and UOG extraction were extensive to good. Their knowledge about how the industry should be regulated was more limited, with 55% of respondents ($n = 11$) rating their knowledge about the regulation of UOG extraction in South Africa as extensive to good, and only 45% ($n = 9$) rating their knowledge about the regulation of UOG extraction internationally as extensive to good. Most were not satisfied with their levels of knowledge of any of these aspects. Most had sourced their information on UOG extraction and fracking from scientific sources in the form of research reports (80%), scholarly articles (75%), and government reports (60%). They consulted popular media sources less extensively.

The respondents were from government, non-governmental organizations (NGOs), groundwater consultancies, and industry. We targeted a

variety of sectors to get different perspectives on the importance of the regulations we proposed and how easy they would be to enforce. In South Africa, there is a complex interplay between these different institutions as regards groundwater protection. The Department of Water and Sanitation has very few groundwater specialists[53,80] as most have moved to consultancy companies[53], but the few who are left must still draft regulations and ensure they are enforced. Academia and consultancies are often called on to assist government in some of its functions[53], so the country does have fairly good groundwater resource management capacity, although most of this capacity is located at the consultancies. It was, therefore, important to elicit the opinions of groundwater specialists from several institutions. The respondents were from the different institutions as follows: consultancies 55% ($n = 11$), government 20% ($n = 4$), educational institutions 10% ($n = 2$), mining, oil and gas industries 10% ($n = 2$) and NGOs 5% ($n = 1$).

Data analysis

We analysed the quantitative data with the statistical package for social sciences version 25. Qualitative data were analysed thematically to add more depth to the quantitative data interpretation and to better understand respondent concerns about our proposed regulations. Qualitative data from open-ended questions was especially useful for gathering information about regulations that might be needed in addition to the ones we proposed. Differences between the respondent groups (based on qualifications, institution, and years of experience) were tested using the Kruskal Wallis statistical test, and the Mann Whitney *U* test was used to identify the specific differences within the groups. We identified significant differences only in the respondents' opinions on the enforcement of regulations and only according to their years of experience. We found that respondents with less than 20 years' experience viewed the enforcement of specific setbacks, BATP regulations, and PID regulations as more difficult than respondents with more than 20 years' experience (see Supplementary Table 3). This could be because in South Africa specialists with fewer years of experience typically work in government institutions and are therefore more aware of the difficulties those institutions currently experience, while those with more years' of experience typically work in consultancy firms. This is confirmed by our biographical data and the 2016 groundwater strategy for South Africa[53] We also assessed whether there were significant differences in respondent views on the institutional capacity to regulate UOG extraction, between a survey that we carried out in 2012 and our 2019 survey, using the Mann Whitney *U* test. There were no significant differences between the two groups in their views on South Africa's capacity to regulate fracking, except that the 2019 group felt that South Africa had a clearer fracking policy than the 2012 group ($U = 134$, $Z = -2.98$, $p = 0.003$). Both the 2012 and 2019 groups felt that South Africa would not be able to effectively regulate fracking.

Limitations

We acknowledge two limitations of our study. One is the small sample size, the reason for which has been explained. Note that our use of percentages to represent this very small sample is not intended as a claim to statistical validity or generalizability. The percentages are used to ease reading and to demonstrate how our survey method might be extrapolated to a larger sample, and in the figures to aid in visual interpretation. Another limitation is the unevenness of the sample, with more than half of the respondents being of one type (11 of the 20 were from consultancies), which could introduce bias.

DATA AVAILABILITY

Datasets related to this study will be made available upon request by the corresponding author, subject to compliance with the University of the Free State research ethics board restrictions on survey data.

Received: 8 June 2021; Accepted: 1 December 2021;
Published online: 19 January 2022

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ACKNOWLEDGEMENTS

We thank the reviewers who contributed to the development of the questionnaire used in this study, and to the groundwater experts who took time to complete the questionnaire.

AUTHOR CONTRIBUTIONS

S.E. conceptualized the research, developed the survey instrument, executed the survey, analysed the data and wrote the manuscript. D.V and J.G. assisted in conceptualization of the research, reviewed the questionnaire and the manuscript and contributed to the writing of the manuscript.

ETHICS STATEMENT

The University of the Free State ethics board approved the survey instrument (UFS-HSD2018/1420). Informed consent was obtained from all respondents. The respondents completed the survey anonymously to ensure adherence to ethical guidelines.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41545-021-00145-y.

Correspondence and requests for materials should be addressed to S. Esterhuyse.