CHAPTER 5

Water Resources

CHAPTER 5:
WATER RESOURCES

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Executive Summary

Water availability/supply for shale gas development (SGD) in the assessment study area is severely constrained. Surface water availability is generally low, with large areas of non-perennial, episodic and ephemeral streams experiencing very high inter-annual variability (Subsection 5.2.3). The surface water resources in the study area are already stressed (and in many areas over-allocated) to meet the demand of existing users. Groundwater recharge is typically low and sporadic, and where groundwater does not already supply 100% of the demand, the development of groundwater resources to meet shortfalls in surface supplies is increasing, particularly during drought years (Subsection 5.2.3.1). The availability of potable groundwater resources in the study area to meet the additional demand of full SGD (beyond exploration) is seriously constrained. There is potential to develop non-potable (brackish or brack) groundwater resources for this purpose at a limited scale (Subsection 5.2.2.2). This, however, will need to take into account potential impacts associated with the transport and storage of this water, as well as potential impacts due to wellfield development.

Water resources monitoring (especially pre-SGD baseline) is an imperative. SGD must not proceed before a comprehensive set of baseline data for the study area has been established (Section 5.8). This must include surface water availability and verification of existing use also to meet environmental requirements, as well as surface water and groundwater quality. Water resource quality monitoring including general and SGD-specific determinands during and after SGD is also important to ensure protection of the water resources. Different levels of baseline information are however required for different stages of SGD – during exploration, for example, the level of baseline data required is less extensive than is required for development activities that entail hydraulic fracturing ("fracking").

Surface spills on-site and along transport networks are the most likely source of contamination (Section 5.5). Impacts that arise from on-site (wellpad) spills and accidental spillages of noxious/toxic material during transport are inevitable. Although spills *per se* are expected to have localised and short-term impacts; their actual location in the landscape will inform the magnitude of their impact. If the spill enters a river system during flood events, downstream impacts can occur.

Cumulative impacts from other activities will compound water scarcity and quality concerns. The study area is also the focus of other potential SGD-related activities such as fracking, road building and workforce accommodation that will place an additional demand on water resources and present a risk of contamination. Unrelated activities such as uranium exploration and mining will compound this demand. These represent cumulative impacts for both water quantity and quality.

Post-SGD legacy impacts will occur. Impacts following full-scale SGD (e.g. from failing/failed spent production wells) are a cumulative and inevitable legacy issue far into the future and relate to the failure of post-SGD production well casings. Where these impacts are traceable (e.g. from monitoring data), containment is feasible following site-specific assessments to identify the most appropriate mitigation measures and monitoring to establish the success of these. However, since they may only arise long after SGD has ceased, there may be concerns over the likelihood of actual detection and the availability of funding for remediation. Such issues would need to be considered in a permit.

Concern of landowners about negative impacts on local domestic/stock water supplies is acknowledged. Local landowners are mainly reliant on groundwater resources for domestic and stock water supplies. The concern about impacts on these resources from SGD is very real and understandable. The measures recommended in the scientific assessment for protecting groundwater resources must address these concerns.

Lack of a comprehensive Reserve determination prevents SGD. A comprehensive determination of the Reserve (for groundwater, surface water and wetlands) for basic human needs and ecological requirements must be carried out before SGD occurs. The authority (Department of Water and Sanitation) responsible for Reserve determinations will not issue water use licences without a comprehensive Reserve determination having been completed (Subsection 5.4.3).

Lack of infrastructure and institutional capacity for water management is a constraint. Insufficient institutional and human resource capacity is a severe constraint to the implementation and execution of a robust and effective water resource monitoring and management programme for SGD. This constraint will apply to regulatory authorities, who often lack the necessary skills and the will to exert enforcement, and less so to the industry, which it is expected will mobilise the necessary resources to meet regulatory requirements in this regard. This constraint is particularly relevant to independent monitoring and evaluation activities directed at ensuring compliance of the SGD industry with the regulatory requirements. Environmental non-compliance could be amplified by poorly capacitated regulators.

Lack of laboratories in South Africa (RSA) for water chemistry analysis is a severe constraint. Although most accredited local (RSA) laboratories are equipped to carry out the more routine water analyses (e.g. major cations and anions), none are capable of analysing for determinands such as $\delta^{11}B$, $^{36}Cl/Cl$, ^{4}H, $^{3}H/^{4}H$, and CH_4. Sufficient lead-in time must be allowed for such facilities to be established prior to baseline monitoring requirements.

SGD provides a learning opportunity that will improve understanding of local water resources. The activities associated with SGD create a substantial opportunity to generate new geoscientific data and information. This will advance an understanding of the geoscience framework (e.g. geology, hydrogeology, geophysics, geochemistry) of the study area. The benefit will extend to the international geoscientific community. The discovery of as yet unknown groundwater resources is a further possibility. Realising this opportunity will proceed whether SGD advances to production stage or not, as the geophysics and exploration drilling will have identified this potential.

CHAPTER 5: WATER RESOURCES

5.1 Introduction and Scope

Water scarcity is a critical issue in South Africa and sources of water for shale gas development (SGD), and the possible effects thereof on water resources, are crucial factors to consider in this assessment. The demand for water would be greatest during the establishment of a production well typically comprising a wellbore with vertical and horizontal sections. The drilling process typically requires ~1 000 cubic metres (m^3), and the hydraulic fracturing ("fracking") process ~16 300 m^3 per well with no water re-use and ~11 150 m^3 with water re-use. Defined by substantial error bounds (±40 to 50%), the fracking water use values are bracketed by the median values reported in Table 5.1. Although the timeframe for this concern spans the establishment and development of each well (typically one month), its long-term impact only ends with completion of the last production well and any repeat fracking activity that may be required in its active lifespan. The availability of water and the impact of its acquisition on existing water resources therefore represent one of two primary concerns. The second revolves around the issue that a variety of chemicals is added to the water used in the drilling and fracking process. These additives serve a number of purposes all aimed at improving the efficiency of the process and the productivity of the completed production well. The escape of any of this water into the environment, either as surface spillage, flowback or as produced water via whatever pathway, as well as the possible entrainment of harmful chemicals that may occur naturally in groundwater at depth, therefore represents the second primary concern for its possible impact on the fitness for use of existing water resources. The timeframe for this concern extends well beyond the productive lifetime of the well and wellfield.

The occurrence and availability of water in the study area varies both spatially and temporally, partly in accordance with rainfall typically expressed as mean annual precipitation (MAP), but also in accordance with the water-bearing properties of the Karoo strata that host the groundwater resources. With a MAP that is generally <300 mm, the western and south-western portions are drier and more arid than the semi-arid eastern portion with a MAP of >300 mm (refer to Figure 1.4 in Burns et al., 2016). Surface water is a scarce resource in the Karoo environment characterised by ephemeral surface water drainages with periodic discharge and an associated low assurance of supply (Figure 5.1). This places a huge value and reliance on groundwater resources. At the same time, the study area straddles several major (primary) catchments (Subsection 5.2.3), which indicates that impacts of various development scenarios on water resource condition may have further-reaching implications for downstream resource users, including natural ecosystems.

The circumstances described above explain the concern for any activity that threatens this resource. The development of a shale gas industry is seen as such a threat. It is attendant on this scientific assessment to evaluate robustly the threat of SGD to the water resources environment. Such assessment must necessarily consider both the quantity and the quality aspects associated with these resources. By their nature, the quantity aspect is more easily addressed than the quality aspect for reasons that will become evident.

Although the discussion of SGD in relation to water resources is arguably one of the more prominent, contentious and emotive of the 17 topics included in the overarching scientific assessment, a focus on key issues must capture and convey the most relevant and appropriate information on this aspect of the scientific assessment within reasonable text constraints. It must necessarily present a synopsis of hydrological, geological, hydrogeological and technical material that establishes a common basis on which is developed the assessment of key potential impacts and associated risk. The scientific assessment must also necessarily rely to some extent on international experience where the shale gas industry has reached maturity and a scale that lends statistical significance and credibility to the manifestation of negative impacts on water resources. Its relevance, however, depends on the extent to which it assesses threats in the context of the existing Karoo water resources environment, e.g. factors such as current and future water availability and use, natural quality constraints, environmental requirements and other hydrophysical limitations.

5.1.1 What is included in this topic?

The 'driving' water resource components comprise rainfall, evaporation, evapotranspiration, runoff and stream discharge, infiltration into the sub-surface, groundwater and its replenishment, hydrological linkages (fluxes) between surface water and groundwater, as well as quality. The 'receiving' components comprise shallow to deep aquifers, downstream water courses including rivers, wetlands and estuaries outside of the study area that may nevertheless be affected by changes in water quality and/or water quantity in the study area, surface storage (reservoirs) containing both surface runoff and pumped groundwater, human and ecosystem dependence in terms of current and future water demand and use, and waste water generation in terms of quantity and quality. The topic also includes groundwater (possibly of poor to very poor quality) occurring at considerable depth in the sub-surface. Fracking technology is increasingly adapting to the use of poor quality water in an effort to limit the impact on better quality water supplies.

In the semi-arid to arid Karoo environment, it is likely that surface water availability for such additional uses is limited (SSI, 2012; Grimmer and Turner, 2013) even without degradation of water resource quality. This issue is discussed, along with the broad implications of alternative water uses for exploration, appraisal, development and production phases of shale gas. Alternative water uses considered include treated waste water, seawater and deep groundwater. Also included are the ancillary threats to water resources posed by industry-related transport activities such as the conveyance of fuels, chemicals and other hazardous materials to site, the storage and handling of these locally together with waste products (e.g. waste water, sludge and brine) generated by on-site activities, and the conveyance of waste products from site. Note however, that whereas the waste component of this scientific assessment (Oelofse et al., 2016) deals with the normal handling of waste passing into and out of the site, this Chapter deals only with the implications of and responses to accidental exposure of surface and/or groundwater resources to contaminants as a result of spillage, leakage or disaster events.

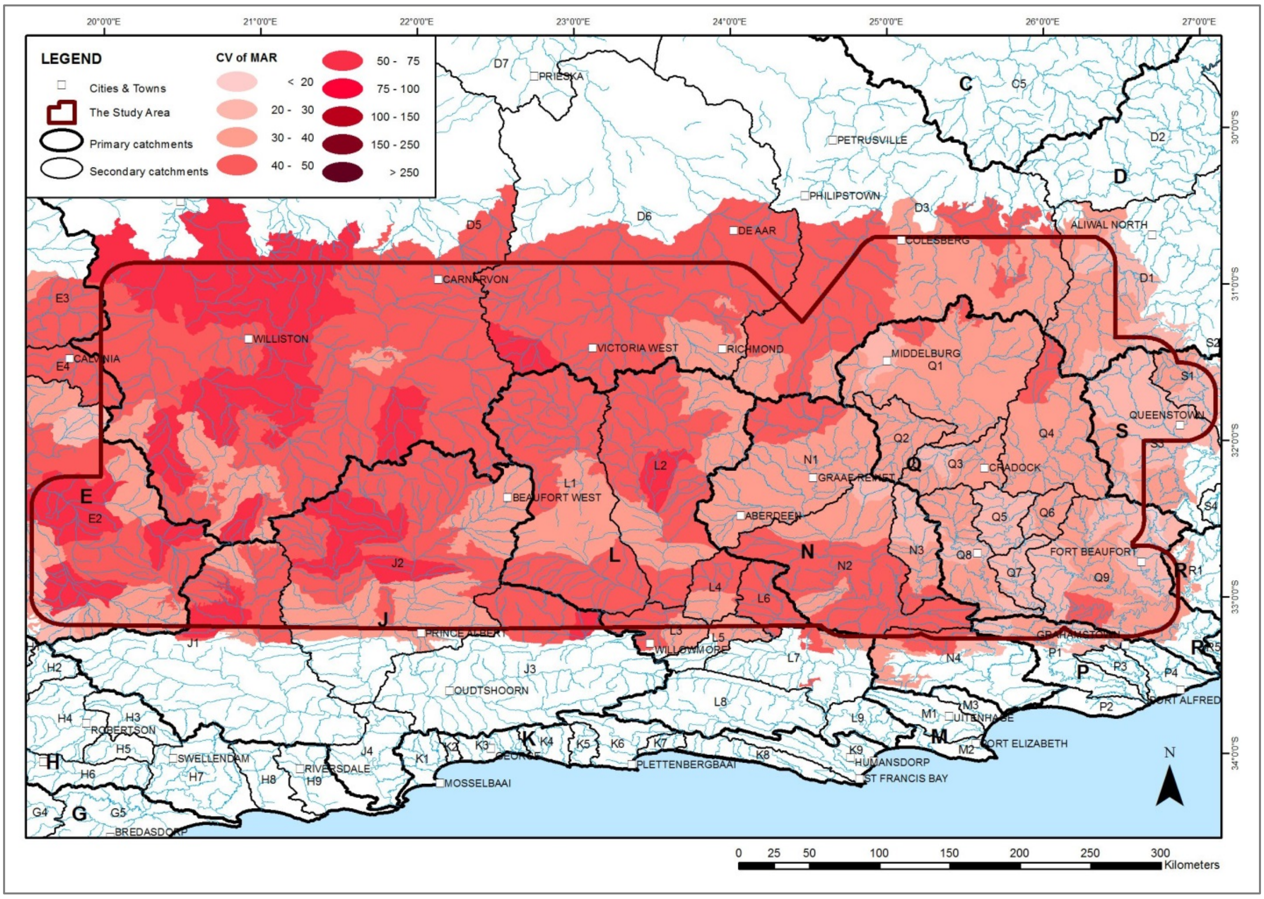

Figure 5.1: Co-efficient of variation (CV) as % of annual rainfall in the study area. The figure illustrates year-to-year rainfall assurance, as follows: the CV is a relative index of variability, expressed as a percentage (Std Dev/Mean*100), allowing a comparison of rainfall CV to streamflow CV. The higher the CV; the more variable and unreliable the year-to-year rainfall. The study area has amongst the highest CV's in SA, particularly in the western two-thirds of the site. Original data sources: Schulze et al. (2010) and Schulze (2012).

Important assumptions regarding spatial limitations for practical implementation of fracking exploration through to production activities, with particular relevance to water resources assessment, include:

- slopes steeper than 10% will not be targeted, even in the exploration phase (Burns et al., 2016); and
- legislated setbacks will be adhered to [e.g. GN R466 of 3 June 2015 in terms of the Minerals and Petroleum Resources Development Act (RSA, 2015a) (Section 122(2)].

5.1.2 Overview of international experience

International experience with SGD on a substantial scale dates back to the 1940's in the United States of America (USA). The USA and Canada currently account for virtually all of the commercially produced shale gas globally (Norton Rose Fulbright, 2013). These industries therefore attract the closest scrutiny for their learning opportunities. The scale of the industry is informed mostly by the

> ***Proppant**: Material, usually sand or ceramic particles, carried by the fracking fluid into a fracture to keep it open when hydraulic pressure is released.*

size of the resource, as technological advances have to a large extent overcome natural limitations. Examples of these are drilling techniques that have overcome constraints on the depth of extraction, directional horizontal drilling, multi-stage fracking and efficacy of drilling and fracturing fluids (including the use of waste water) and proppants to fracture the reservoir strata and release trapped oil and gas. The mature USA and Canadian industries benefitted from already existing conventional oil and gas infrastructure, allowing SGD and production to focus attention and costs on the upstream infrastructure. SGD in the Karoo does not provide such benefit. It must start from scratch, and would require extensive development of infrastructure (roads, services, etc.) along with direct development-associated activities.

Fracking varies in its water requirements (Burns et al., 2016, Subsection 4.3.2.2.1), the amount and type of chemicals used, and the quantity and quality of waste water generated (Cooley and Donnelly, 2012). These variations can occur even between neighbouring wells (Nicot et al., 2011) and, as shown by Nicot et al. (op cit), varies between four different shale gas resources in the semi-arid environment of Texas (Table 5.1). Cooley and Donnelly (2012) report the conflict between existing water use and shale gas production created by a major drought in Texas in 2011 that precipitated the imposition of mandatory water use reductions. The volume of waste water (flowback and produced water) that is generated during full scale SGD is similarly characterised by large uncertainty. Flowback can range from 10 to 80% (Broomfield, 2012; Grant and Chrisholm, 2014) of that injected during fracking. Produced water, although typically in the order of 1 to 2 m^3/d (Rahm et al., 2013), can be produced for the lifetime (many years and more) of a production well.

The scarcity of surface water resources in the semi-arid and arid Karoo landscape suggests that the learning experience from the wetter North American plays has limited relevance to this scientific assessment. The Barnett Shale in Texas and the Permian Basin of western Texas and New Mexico, both are characterised by semi-arid to arid climates, provide the closest developed international proxies for the Karoo Basin.

Table 5.1: Water requirement estimates for fracking in four Texas shale gas resources (from Cooley and Donnelly, 2012).

Shale gas resource	Water requirement (m^3 per well)[(1)]		
	Low-end estimate	**Median**	**High-end estimate**
Barnett Shale	<3 800	9 800	>30 300
Haynesville and Bossier Shale	<3 800	20 800 to 22 700	>37 900
Eagle Ford Shale	3 800	22 700 to 24 600	49 200
Woodford, Pearsall and Barnett-PB Shale	<3 800	2 800 to 3 800	<18 900
(1) Values rounded off to nearest 100			

Note however that these shale formations are at different depths to those in the Karoo, and the data presented in this table may not therefore be representative of the actual water requirements for fracking of Karoo systems, given that water requirements are a function of depth and other factors.

5.2 Characterising features of the Karoo environment

5.2.1 Geology

A description of the key geological features of the Karoo Basin is provided in Section 1.3.1 of Burns et al. (2016). Familiarisation with this description will facilitate an understanding of the concepts and relationships that inform the association between geology, shale gas and groundwater that is discussed in this Chapter. The mudstones and sandstones of the Adelaide Subgroup at the base of the Beaufort Group succession of sedimentary strata represent in surface extent the main rock types in the study area. Covering ~87% of the landscape; these strata host the shallow aquifers that provide groundwater primarily for human and livestock consumption in the semi-arid to arid environment. This function is generally enhanced in the presence of dolerite intrusions in the form of dykes and sills (Subsection 1.3.1.2 of Burns et al. (2016), and is identified as a unique feature of the Karoo Basin that has a potential impact on gas reserves and contaminant migration to surface. The sedimentary rocks of the Ecca Group cover a further ~6% of the study area.

> ***Aquifer****: Part of a formation, a formation or a group of formations that is/are capable of both storing and transmitting groundwater, by virtue of possessing sufficient saturated and interconnected porous and/or permeable material, directly to a borehole, well or spring in sufficient quantities for a required use.*

In agreement with Rosewarne et al. (2013), who recognise a western, a central and an eastern subarea; this study recognises an additional southern subarea (Figure 5.2). Each subarea is characterised by distinguishing lithological and hydrogeological attributes. The subdivision also recognises physiographic factors such as the Great Escarpment. Changes from one subarea to another are mostly gradational.

- *Western subarea.* Dolerite intrusions in the form of sills and dykes occur in abundance throughout the western area. The intrusions represent the main targets for groundwater exploration. The high ridges (inselbergs) which characterise large parts of the area are the result of erosion resistant dolerite forming a protective capping for the underlying sedimentary strata. The target shale gas horizons deepen westwards and southwards from ~500 m along the western and northern margin, to >2 000 m below surface.

- *Central subarea.* The area is characterised by horizontal to sub-horizontal strata. The horizontal bedding gives rise to the expansive landscape of flat to gently undulating plateaus. The landscape becomes more hilly east of Richmond. A greater density of dolerite sills and dykes occurs to the north and central parts of the area, again representing main targets for groundwater exploration. The topography is again the result of erosion resistant dolerite forming cappings to these features and ring complexes which give rise to circular shaped basins. The target shale gas horizons diminish in depth northwards from ~2 000 m along the southern margin to ~1 000 m along the northern margin.

- *Eastern subarea.* North of the towns of Somerset East and Adelaide dolerite intrusions (sills and dykes) occur in abundance. The target shale gas horizons occur at depths of ~3 500 m in the southern part, becoming shallower in a north-easterly direction to ~1 000 m below surface.

- *Southern subarea.* A key feature of this area is a general absence of dolerite intrusions, except in the very north-east of the area, and the proximity to the Cape Fold Belt (CFB). Proximity to the CFB resulted in this area being structurally more complex than the other three subareas, with folding and fracturing of the rock layers. The trend of the fold axes is approximately east-west, with the steepest bedding dip angles in the south, moderating rapidly to the north before the Great Escarpment. The target shale gas horizons for the most part occur >2 000 m below surface.

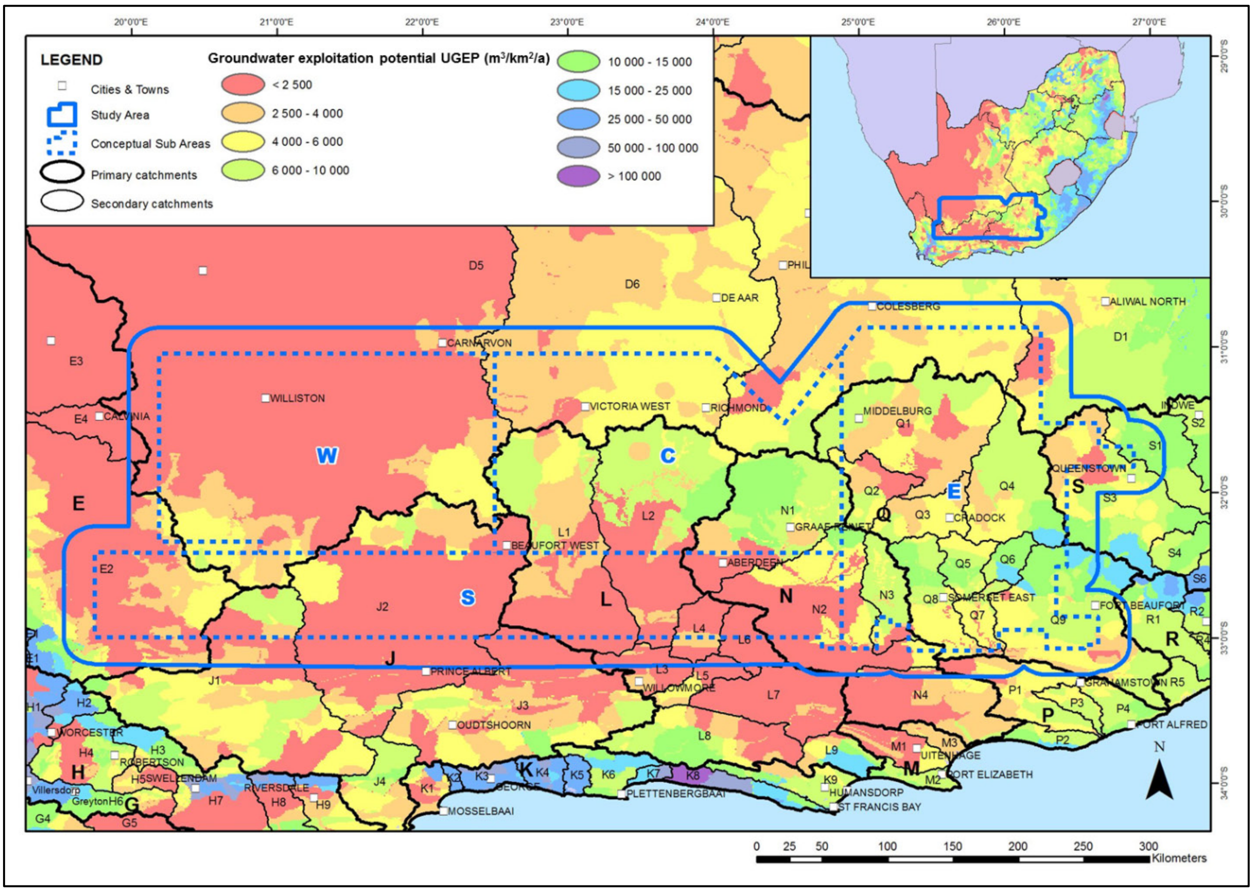

Figure 5.2: Utilisable Groundwater Exploitation Potential. The figure shows the subdivision of the study area into four subareas identified as W (western), C (central), E (eastern) and S (southern) distinguished on the basis of lithological, hydrogeological and morphological factors; boundaries are gradational (adapted from Rosewarne et al., 2013): base map shows the utilisable groundwater exploitation potential in the study area with inset map for national context (after DWAF, 2005).

5.2.2 Groundwater

5.2.2.1 Occurrence

Dolerite intrusions in the form of dykes and sills and ring complexes are intrinsic to groundwater occurrence in the broader Karoo environment (Chevallier et al., 2001). As already mentioned, these structures represent the main targets for scientific groundwater exploration, with dykes in particular being the feature most commonly targeted by landowners for successful borehole siting. These circumstances have resulted in a comprehensive assessment of these features, on the basis of which the following groupings are recognised:

- East-west striking dykes, some of which are extensive and continue over 500 km. These intruded along major lateral east-west dislocation/shear zones, and are accompanied by north-west and north-east trending sympathetic shears. They are thought to represent feeder dykes extending to the base of the Karoo Supergroup.
- North-northwest striking dykes, which are also regionally extensive and regularly spaced from east to west across the Karoo landscape. Their trend is curvilinear, varying from west-northwest in the south to north-south in the north.
- Sill and ring complexes are prominent features of both the western and eastern Karoo, where they are well developed in the upper Ecca Group sediments. The geometry of these features ranges from tabular to bowl-shaped, and may comprise a multi-level stacking in nested groupings. Many of these structures are fed by arcuate dykes (Chevallier et al., 2001). In their simplest expression, the sills form the resistant caprock that characterises the flat-topped koppies (hillocks) of the Karoo landscape.

An association between lithology and dolerite distribution is inferred from the observation by Woodford et al. (2001) of a sharp decrease in intrusion density at the boundary between the lower and upper Ecca strata. This boundary corresponds to the appearance of the first sandstone units of the Karoo Supergroup. The majority of the dykes are stratabound and concentrated in the upper Ecca and Beaufort group sandstones.

In broad terms the shallow aquifer is mainly associated with the weathered and/or fractured sedimentary strata (mudstone and sandstone) of the Beaufort Group, and the deep aquifer with fractured Ecca Group and Dwyka Group strata, and possibly also underlying basement strata. The intermediate aquifer most likely associated with the groundwater of 'mixed' chemical composition (Murray et al., 2015), is not readily positioned in lithostratigraphic terms. The aquifer yield is derived from the utilisable groundwater exploitation potential (UGEP) estimates produced by the then Department of Water Affairs and Forestry (DWAF) GRAII Project (DWAF 2005) and as shown in Figure 5.2. These estimates are based on average input values and therefore will not vary significantly over time as they are based on long-term records (i.e. mean annual rainfall, recharge, and average water levels). The UGEP provides an estimate of the maximum volume ($m^3/km^2/a$) of groundwater that is potentially available for abstraction under natural conditions (i.e. no abstraction) and normal rainfall conditions. The UGEP figures illustrate the fact

> ***Lithostratigraphic:*** *Combination of the terms lithology describing rock type, and stratigraphy describing position in the geologic record.*

that aquifer yields increase from the western to the eastern area. Water levels become shallower, recharge increases and water quality improves in this direction and also from south to north in the eastern area. These trends are reasonably attributed to factors such as the increase in rainfall, the greater proportion of sandstones relative to siltstone/mudstone strata, and the preponderance of dolerite intrusions to the east.

The windpump is synonymous with the Karoo environment, and is a constant reminder of the value of groundwater in this landscape. Successful boreholes are often associated with intrusions of dolerite into the sedimentary strata in the form of vertical to sub-vertical dykes and/or horizontal to sub-horizontal sill and ring-complex structures (Chevallier et al., 2001; Woodford and Chevallier, 2002). The hydrogeological maps 3117 Calvinia (RSA, 2002a), 3122 Beaufort West (RSA, 2002b) and 3126 Queenstown (RSA, 1997a) assign a median yield in the range 0.5 to 2 litres per second (L/s) for a successful borehole across much of these map areas in the study area, with total dissolved solids (TDS) levels in the range 500 to 2 100 milligrams per litre (mg/L) , nitrate levels >10 mg/L (as N) and fluoride levels >1.5 mg/L being a common occurrence in this groundwater. The nitrate and fluoride levels define the recommended operational limit (for N) and maximum allowable level (for F) for limited duration as given in the earlier South African National Standards (SANS) 241 national drinking water standard. The most recent revision (SANS, 2015a; 2015b) reports a standard limit of ≤11 mg/L for nitrate as N, with that for fluoride unchanged at 1.5 mg/L.

Salinity: *A measure of the total dissolved solids (TDS) concentration expressed as electrical conductivity (EC) with the unit mS/m (milliSiemens per metre). The ratio of TDS to EC provides a useful factor to estimate TDS (as mg/L) from EC (as mS/m). The ratio for natural water typically falls in the range 5.5 to 7.5 (Hem, 1985). More acidic, poorly buffered and/or more saline water will differ from this, with higher ratio values generally associated with water containing higher sulfate levels. For example, the sulfate-rich acid mine water of the West Rand Goldfield is characterised by a ratio of 10 to 12.*

Site specific scientific groundwater investigations generally yield more productive boreholes than are reflected in the hydrogeological maps. The scientifically-based (geophysical) siting of 67 water exploration boreholes with a median depth of 240 m targeting dolerite structures around Victoria West (Chevallier et al., 2001) returned a median blowout yield of 2.4 L/s and a median TDS concentration of ~420 mg/L. Similarly, groundwater investigations carried out in the Beaufort West area in the late-1970's (BRGM, 1977) identified an alluvial aquifer associated with the Sout River. This intergranular primary aquifer comprises unconsolidated alluvial material >10 m thick supporting borehole yields of ~5.5 L/s and an electrical conductivity (EC) of >500 mS/m. These circumstances resulted in the establishment of a wellfield. More recently, SRK Consulting (SRK, 2007; 2008) identified a productive fractured rock aquifer in the Ryst Kuil area. Developed in channel sandstone up to 45 m thick, this aquifer supported exploration boreholes with yields in the range 3.5 to 26.7 L/s (SRK, 2008) producing groundwater with a salinity of <150 mS/m. Given the arid nature of the area and the impact of drought, long-term sustainable yields are likely to be more conservative but still significant.

Standard limit: *Acceptable health risk for consumption of an average of 2 litres of water per day for 70 years by a person weighing 60 kg (SANS, 2015a).*

The natural occurrence of groundwater in the study area is rendered in greater detail in Figure 5.3 on the basis of the aquifer classification protocol followed for the Department of Water and Sanitation (DWS) 1:500 000 scale hydrogeological map series. Figure 5.3 indicates that most of the study area is characterised as being underlain by fractured aquifers supporting boreholes with a median yield in the range 0.5 to 2 L/s. Areas of higher yielding boreholes occur around Beaufort West and Aberdeen, amongst others. Intergranular and fractured aquifers are prominent in the north-eastern and eastern portions of the study area (e.g. around Richmond and Queenstown). As the data also provide an indication of groundwater availability, this aspect is discussed in the context of demand in Subsection 5.3.1.

Understanding and evaluating the threat of SGD to the water resources of the Karoo is undoubtedly confounded by the complexity of the surface water and groundwater environments. It is therefore inevitable that a varying degree of uncertainty will apply to such understanding and evaluation, depending on the availability of data and the level of unobservable and therefore inferred complexity in the absence of monitoring data. For instance groundwater level and temperature monitoring of the Ryst Kuil aquifer in the period 2007 to 2010 (SRK, 2010) indicated recharge in some areas and no recharge in others. The areas of recharge could be linked to sites close to rivers and dams excavated to collect some surface run-off. Groundwater levels in the 3 year period of record declined in the range 0.4 to >2 m in the areas of no recharge.

DWS aquifer classification: *Four aquifer types (modes of groundwater occurrence) are recognised as follows:*

Intergranular .... a
Fractured .... b
Karst c
Intergranular & fractured .... d

Five median yield ranges (excluding dry boreholes) are recognised as follows:
0 to 0.1 L/s 1
0.1 to 0.5 L/s 2
0.5 to 2 L/s 3
2 to 5 L/s 4
>5 L/s 5

The alpha-numeric combination of the above, e.g. b3, classifies both the aquifer type and groundwater availability, and lends itself to colour-coding as shown in Figure 5.3.

5.2.2.2 Water quality

Rosewarne et al. (2013) report that sodium concentrations in the shallow groundwater decrease from the drier western portion to the wetter eastern portion of the Karoo, an observation supported by Murray et al. (2015). The 'shallow' groundwater is typically characterised as cool (<24°C) and fresh to slightly saline (brackish) (RSA, 2002a; RSA, 2002b; Murray et al., 2015). The occurrence of groundwater at much greater depth (>1 000 m) is known from a handful of ultra-deep (up to ~4 000 m) boreholes. The 'deep' groundwater resources are generally characterised by warm (>24°C) to hot (>34°C) (Murray et al., 2015) and moderately saline (highly brackish) water. In some instances the confining pressure of overlying strata causes the water to rise to surface, resulting in free-flowing (artesian) borehole discharge similar to thermal springs. The hydrostatic pressure is typically shut in by fitting the borehole with a gate valve and pressure gauge. Despite such measure, the Southern oil Exploration Corporation (SOEKOR) well SA 1/66 had stopped flowing by the time Murray et al.

Groundwater temperature: *Kent (1950) proposed the following classification for groundwater temperature:*

Warm .... 25° to 37°C
Hot .... 37° to 50°C
Scalding .... >50°C

(2015) visited the site in July 2014 for sampling purposes. The Institute for Groundwater Studies (IGS) at the University of the Free State (UFS) has previously successfully sampled the well in November 2012 and September 2013. The more recent cessation of artesian flow suggests that pressure relief occurred via another pathway in the sub-surface. Murray et al. (2015) concluded that the 2013 chemistry already reflected a mixture of deep and shallow groundwater. It is not improbable that moderately saline (highly brackish) groundwater might be exploited by the shale gas industry for drilling and fracking water supply purposes, although it should be considered that the US Bureau for Land Management (BLM) attempted to set a lower TDS limit of 10 000 mg/L for such use in the Pavillion Field of Wyoming (DiGiulio and Jackson, 2016).

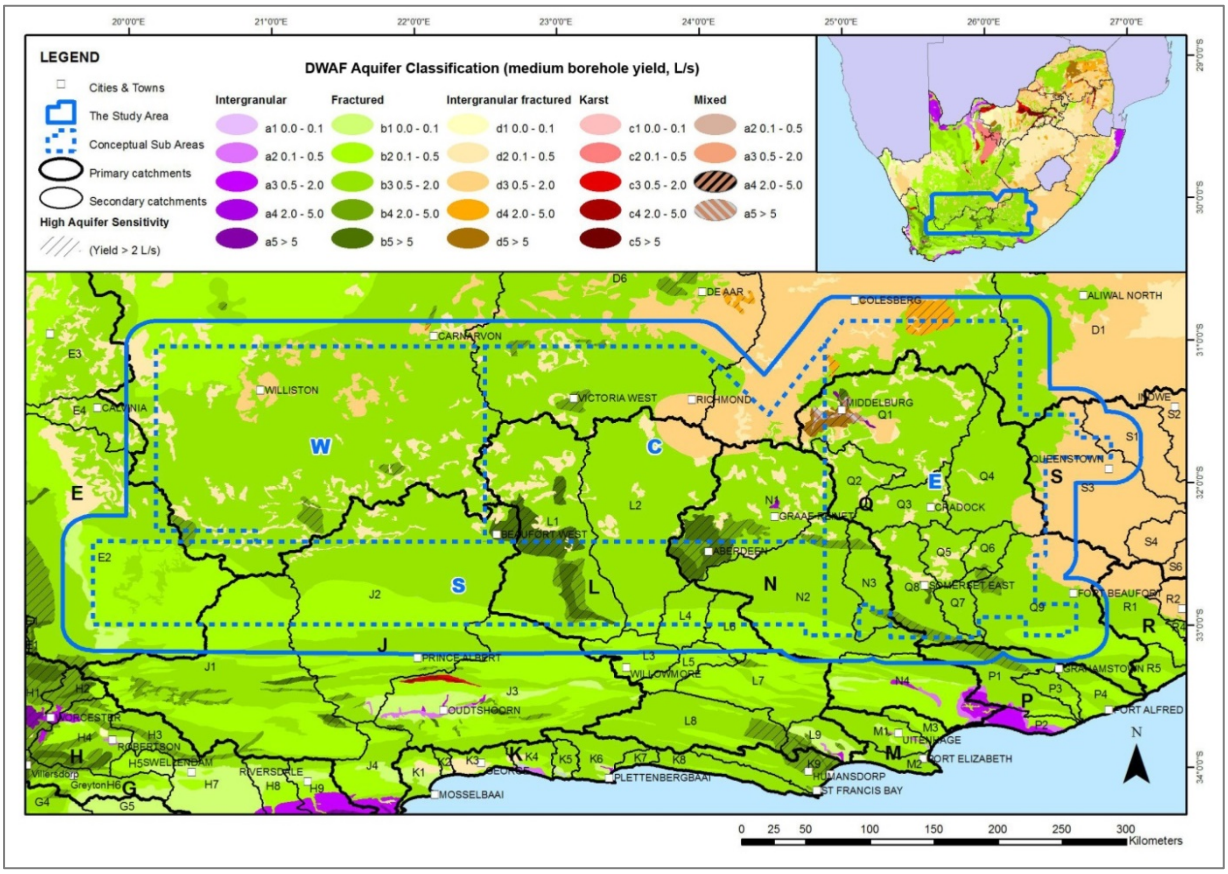

Figure 5.3: Groundwater occurrence in the study area (after RSA, 1997a; 2002a and 2002b).

> ***Brack water:*** *Salty tasting water caused by a higher concentration of dissolved mineral elements (e.g. calcium, magnesium, sodium, chloride) collectively described as total dissolved solids (TDS). The TDS concentration is used to describe the degree of salinity (brackishness). The following classifications are two examples of many.*
>
> | *Hem (1985)* | *TDS (mg/L)* |
> |---|---|
> | *Fresh* | *<1 000* |
> | *Slightly saline* | *1 000 to 3 000* |
> | *Moderately saline* | *3 000 to 10 000* |
> | *Very saline* | *10 000 to 35 000* |
> | *Briny* | *>35 000* |
> | *Sea water* | *~34 000* |
>
> | *King (2012)* | *TDS (mg/L)* |
> |---|---|
> | *Fresh* | *<1 000* |
> | *Brackish* | *1 000 to 5 000* |
> | *Highly brackish* | *5 000 to 15 000* |
> | *Saline* | *15 000 to 30 000* |
> | *Sea water* | *30 000 to 40 000* |
> | *Brine* | *40 000 to >300 000* |

> ***CIMERA-KARIN:*** *The Centre for Excellence for Integrated Mineral and Energy Resource Analysis (CIMERA) is a Department of Science and Technology and National Research Foundation facility tasked with managing the Karoo Research Initiative (KARIN) programme. This programme is an academic study of the geology of the Karoo Supergroup, with special reference to its shale gas potential, by geoscientists from six of South Africa's leading universities, Keele University in the United Kingdom, and the South African Council for Geosciences (De Kock et al., 2016).*
>
> *The principal aim of KARIN is to explore the southern Karoo Basin through the extraction of deep drill cores. To this end, the initiative has recently completed two deep boreholes, one near Ceres in the Tankwa Karoo (borehole KFZ-1) west of the assessment study area to a depth of 671 m, and the other near Willowvale (borehole KWV-1) in the Eastern Cape to a depth of 2 350 m.*

Both Rosewarne et al. (2013) and Vermeulen (2012) also recognise an 'intermediate' aquifer arbitrarily assigned to the depth interval 300 to 1 000 m below surface. The groundwater of 'mixed' chemical composition recognised by Murray et al. (2015) is considered to derive from this interval. An analysis of water samples drawn from 20 boreholes/springs led Murray et al. (2015) to categorise these into three distinct groups, viz. seven deep and eight shallow with confidence, relegating five to a 'mixed' group on the basis of hydrochemical differences, suggesting a correlation with the similar distinction drawn between aquifers. It is not yet possible to associate the intermediate/mixed and deep aquifers with either a specific lithology (formation) or water chemistry. The ca. 1960's SOEKOR boreholes indicate that one or more water strikes of 0.5 to 2 L/s might be encountered at any depth in the Karoo sedimentary package (Rosewarne et al., 2013). Most recently, the CIMERA-KARIN borehole KZF-1 produced 6.7 L/s of fresh (TDS ~330 mg/L) warm (34.4°C) artesian groundwater at a depth of ~671 m below surface (De Kock et al., 2016) from the Dwyka Group glacial deposits underlying the target shale gas horizon (the Whitehill Formation). The TDS of this groundwater suggests that it may derive (at least in part) from the basal quarzitic strata of the Table Mountain Group that outcrop to the west in the north-western limb of the CFB represented by the Skurweberg mountain range, amongst others. The artesian water produced by KARIN borehole KFZ-1 (De Kock et al., 2016) is an example of groundwater generated in the exploration (pre-development) phase of SGD. The chemical composition of this water will reflect the presence of naturally occurring elements associated with the formation(s) producing this water.

An analysis of groundwater chemistry data associated with each of the subareas recognised in the study area (Section 5.2.1 and Figure 5.2) indicates that each of these areas might also be characterised on the basis of slightly different chemical compositions. These differences are revealed by the 'footprints' that encompass the position of water analyses plotted on a Piper diagram (Figure 5.4). The positions of the southern subarea analyses are shown to illustrate the derivation of the 'footprints'. The footprints indicate a greater difference in groundwater chemistry in the eastern and western subareas compared to the central and southern areas. This is to be expected given the climatic differences that exist between these two subareas (Section 5.2.1). The 'tighter' grouping of the southern subarea data, including the smaller difference in chloride (compared say to the western subarea), is considered to reflect the absence of dolerite intrusion influence on groundwater chemistry. Clear separation of these footprints with that of 'deep' groundwater (from Murray et al., 2015) is evident.

Steyl et al. (2012) report that the results of various geochemical studies of fine-grained sedimentary rocks of the Karoo Supergroup show that the shales are not enriched in possibly "dangerous" elements, including uranium. Murray et al. (2015) identified higher uranium concentrations in the range 0.002 to 0.041 mg/L in the 'shallow' groundwater than that in warm springwaters rising from a maximum depth of ~1 000 m. Uranium occurs quite commonly in the south-western part of the Karoo Basin. The combined extent of these occurrences is sufficient to define the so-called Karoo Uranium (metallogenic) Province, described by Cole et al. (1991) as extending from the north-eastern part of the Western Cape Province across the south-eastern part of the Northern Cape into the southern Free State. Four orebodies were subject to feasibility studies in the late 1970's. One of these, located 42 km west-southwest of Beaufort West, showed an average ore grade of 1.5 kg/t at a depth of 13 m (Cole, 1998). In a study focused specifically on the incidence of naturally occurring hazardous trace elements in groundwater nationally, Tarras-Wahlberg et al. (2008) report concentrations of up to 0.539 mg/L in groundwater taken from old uranium exploration boreholes in proximity to uranium deposits with an average grade of 4.1 kg/t around Beaufort West. Concentrations of <0.016 mg/L were found in water supply boreholes in the same area. Similarly, Vogel et al. (1980) found ^{238}U levels in the range 0.001 to 0.044 mg/L from 9 boreholes in the Beaufort West area. These values are similar to those reported by Murray et al. (2015). The national drinking water standard for uranium is ≤0.03 mg/L (SANS, 2015a; 2015b).

***Uranium**: In its natural state, uranium (U) occurs mainly as the radioactive isotope uranium-238 (^{238}U), which represents ~99.3% of the natural abundance of U. It is extracted for commercial purposes from U-bearing minerals such as uraninite (pitchblende). In the Karoo, the U occurs as shallow tabular ore bodies in association with sandstones of the Adelaide Subgroup, Beaufort Group (Cole, 1998). Uranium is highly soluble in water, its dissolution, transport and precipitation in a groundwater system being controlled by changes (often small) in oxidation-reduction (redox) conditions. Uranyl species (e.g. UO_2, UO_2CO_3) are especially mobile in oxidizing environments (Domenico and Schwartz, 1998) at both alkaline and acidic pH conditions.*

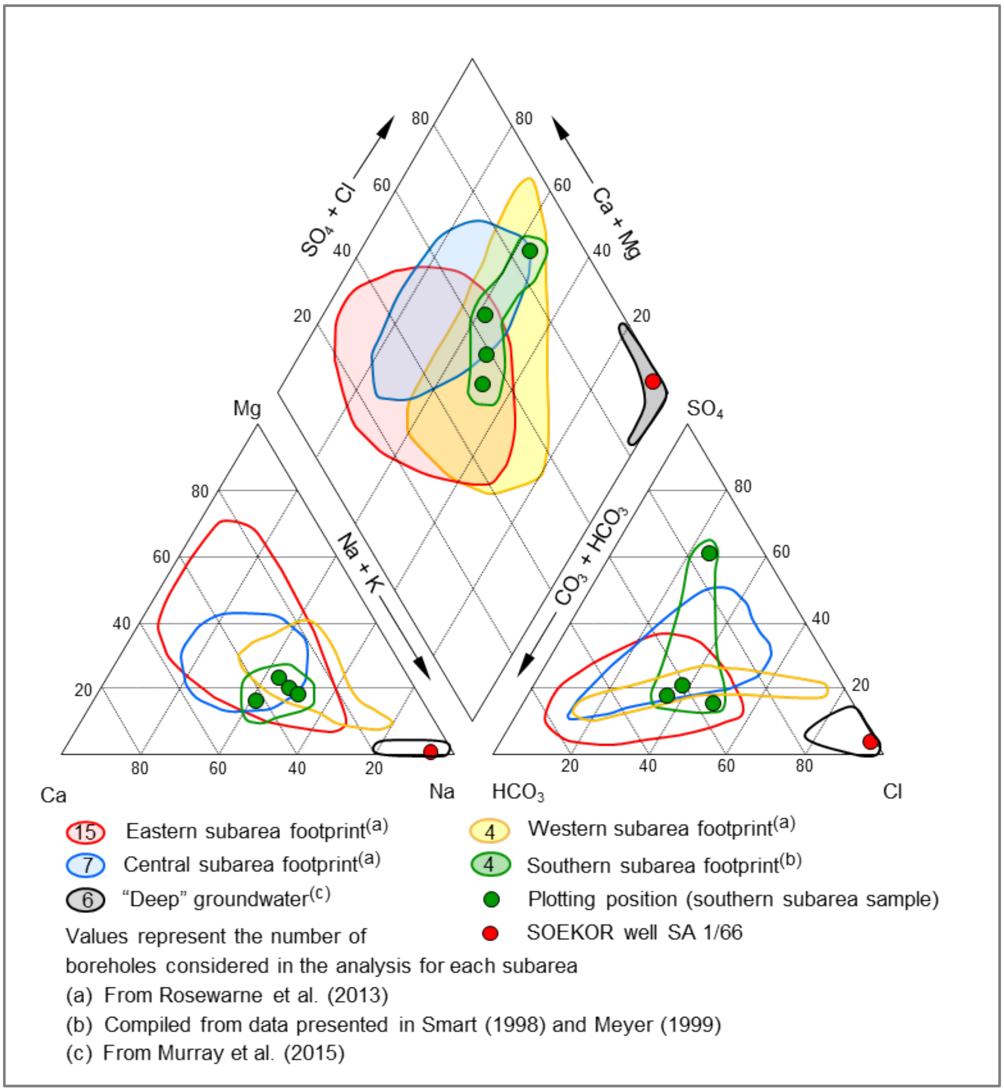

Figure 5.4: Characterisation of shallow groundwater chemical composition between the four subareas recognised in the study area compared to 'deep' groundwater as reflected in a Piper diagram; southern subarea analysis excludes groundwater from the basal Dwyka Group, which varies considerably from fresh to brack.

The uranium deposits are also associated with elevated arsenic concentrations in groundwater. Sami and Druzynski (2003) report concentrations between 0.13 and 0.3 mg/L from 9 boreholes in the south-western Karoo near Beaufort West, while Tarras-Wahlberg et al. (2008) report concentrations of up to 0.082 mg/L in water sampled from exploration boreholes near Beaufort West. These authors also report concentrations of 0.14 to 0.2 mg/L from three boreholes penetrating black carbonaceous shale (probably the Whitehill Formation) north of Calvinia. Murray et al. (2015) report concentrations of 0.001 and 0.009 mg/L in the warm (~30°C) Cradock Spa springwater, and of ~0.02 mg/L for shallow groundwater from a borehole north of Cradock. Most of these levels exceed the limit of ≤0.01 mg/L set by the national drinking water standard (SANS, 2015a; 2015b).

Similar circumstances as described for uranium apply to radon-222 (^{222}Rn), the daughter of radium-226 (^{226}Ra) in the decay chain with ^{238}U as parent. Vogel et al. (1980) report ^{222}Rn activity levels in the range 30 - 128 Bq/L from 14 boreholes in the Beaufort West area. At a more regional scale, Murray et al. (2015) report ^{222}Rn values in the range 1.3 - 58 Bq/L for deep groundwater from six sources, and 14 - 163 Bq/L for shallow groundwater from eight sources. Although the indications are that neither ^{238}U nor ^{222}Rn (and by association ^{226}Ra) represent elements of significant concern for SGD, further geochemical characterisation of the shale gas-bearing strata also in regard to these radionuclides is advisable during the "initial exploration and drilling phase" (Steyl et al., 2012). The impact of chemicals introduced during fracking on the mobility and availability of naturally occurring radioactive materials (NORMs) is, however, unknown and will require evaluation by the industry. Analysis of gross alpha activity and gross beta activity in drill cuttings, flowback and produced water serves as an adequate screening tool to assess whether further characterisation of radioactive material (e.g. for waste disposal considerations) would be required (New York State Department of Health (NYSDOH), 2009). Baseline sampling of water supply boreholes for gross alpha and gross beta activities as well as for NORMS and arsenic is equally advisable.

Talma and Esterhuyse (2015) report the fairly common occurrence of methane (CH_4), a colourless and odourless gas, in groundwater from boreholes and springs in the Karoo environment. These occurrences are associated with both deep and shallow sources (based on water temperature), and occur both north and south of the Great Escarpment. It would also appear that methane emanations are not conditional on the presence of dolerite intrusions (Talma and Esterhuyse, 2015). Methane results presented by Murray et al. (2015) indicate a mean concentration of 17.9 cm^3/kg for six 'deep', 6.4 cm^3/kg for five 'mixed' and 1.9 cm^3/kg for eight 'shallow' groundwater samples. A study by Siegel et al. (2015) of thousands of domestic boreholes in proximity to hundreds of pre-existing oil and gas wells concluded that there is no significant correlation between dissolved methane levels in groundwater and proximity to nearby oil and gas wells. Nevertheless, the inclusion of CH_4 and related diagnostic isotope analyses (^{12}C, ^{13}C, ^{1}H and ^{2}H, amongst others) in the recommended baseline studies is advocated.

5.2.2.3 <u>Contextual discussion</u>

It has been noted that SGD in the USA often appears to be associated with brines with produced water TDS values in the range of 60 000 to 180 000 mg/L (McLaughlin, 2013) and even >250 000 mg/L (Osborn et al., 2011). By contrast, the highest TDS recorded from deep drilling in the Karoo is ~10 000 mg/L (Rosewarne et al., 2013; Murray et al., 2015). This is not much higher than that of some naturally occurring moderately saline groundwater in the Karoo, and might explain why Murray et al. (2015) do not recognise TDS as an indicator of deep groundwater in the Karoo region. The differences in groundwater quality at shallow and intermediate depth is illustrated by the field results from KARIN borehole KZF-1, with groundwater from a depth of ~83 m having a pH of 8.9, a temperature of 25.8°C and an electrical conductivity of ~73 mS/m compared to the pH of 8.3, temperature of 34.4°C and electrical conductivity of ~48 mS/m for groundwater from a depth of 671 m (De Kock et al., 2016).

A flow pathway that has generated considerable attention in the shale gas debate is that of possible hydraulic linkage between the shale gas strata and 'shallow' groundwater resources. This debate is fuelled by the network of structures represented by the dyke and sill intrusions. Rosewarne and Goes (2012) suggests that it is unlikely that potential conduits such as faults and dykes extending from depth to surface remain unmapped. However, 'blind' features that terminate below or in the shallow aquifer could exist, and some mapped geophysical anomalies might correlate to these. The North American experience is based on the presence of faults rather than dykes, and is further confounded by the existence of many and more old oil and gas wells dating back decades, and which represent potential artificial pathways for upward migration of natural and introduced contaminants.

The Aliwal North thermal spring, with a temperature of 37ºC, represents the deepest known groundwater circulation of ~1 100 m below surface based on a geothermal gradient of 30ºC per 1 000 m. This spring discharges groundwater with a TDS of ~1 200 mg/L at a rate of 44 L/s. Evidence provided by the SOEKOR wells SA 1/66, KL 1/65 and VR 1/66 in the southern subarea (Figure 5.2), i.e. below the Great Escarpment, indicates open fractures at depths >4 000 m producing artesian flows of up to 3 L/s, TDS of up to 10 000 mg/L and temperature of up to 76ºC (Kent 1969). The water intercepts in the Dwyka and Witteberg Group strata suggests a more complex groundwater environment and has implications for potential migratory pathways for contaminants from depth to the near-surface (shallow aquifer) and surface environments. The drilling record of KARIN borehole KZF-1 (De Kock et al., 2016) has also proven insightful in regard to hydrogeologically significant aspects of Karoo strata with depth below surface. Beyond the expected presence of a 'typical' shallow fractured aquifer extending to a depth of ~60 m, the record shows the following:

- interception of a dry fracture at a depth of ~82 m that resulted in total circulation loss of drilling fluid;
- occurrence of fault zones at depths of ~450 m and ~480 m; and
- water strikes at depths of 558 m (freshwater), ~626 m (slightly sulphurous water) and ~670 m (6.7 L/s freshwater).

These observations reveal the hydrogeological complexity that might be encountered during SGD, and which represent a mixture of associated opportunities and threats. Opportunities take the form of 'discovered' groundwater occurrences that might be used for community water supply. Threats are embodied in all of the listed items that potentially represent horizons susceptible and vulnerable to intrusion by flowback, produced water and shale gas in the event of casing failure Subsection 5.5.1). Uncertainty also exists regarding an understanding of the stress-strain fields at depth. For example, Coblentz and Sandiford (1994) report large extensional stresses present in the lithosphere beneath southern Africa, which circumstances might have implications for the 'frackability' of proximal overlying strata such as the Whitehill Formation.

The vulnerability information of shallow groundwater resources to contamination from surface sources have been rendered nationally in the GRAII (DWAF, 2005) based on the DRASTIC algorithm (Aller et al., 1987). This is shown in Figure 5.5, which indicates a low to medium vulnerability across most of the study area, with smaller areas of high vulnerability around Beaufort West.

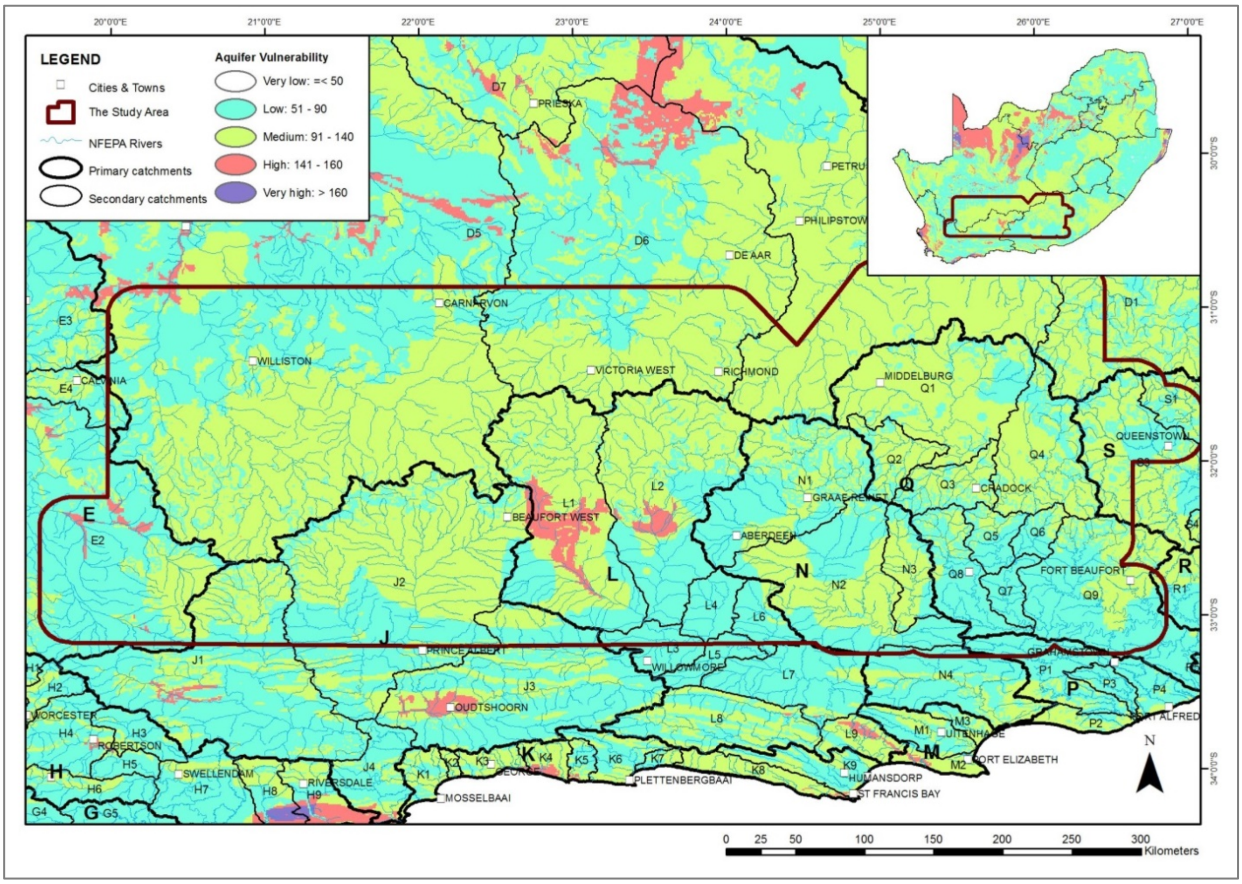

Figure 5.5: Shallow groundwater vulnerability rating (from Esterhuyse et al., 2014).

The vulnerability of the shallow groundwater resources to potential contamination from depth is rendered in Figure 5.6. In the light of sparse information regarding deep groundwater occurrence, known macro-features of the geological environment have been used to derive the qualitative vulnerability assessment based on the following considerations.

An area of **high vulnerability** in the south which is marked by the absence of dolerite intrusions. Karoo strata (including the target shale gas reservoir formations) north of the CFB (not shown) are folded and fractured, with groundwater intercepts being recorded up to a depth of >4 000 m. The Great Escarpment is taken to mark the northern limit of deep artesian flow. The area south of the Great Escarpment is underlain by rocks of the Cape Supergroup (mainly the Table Mountain Group and Witteberg Group quartzitic sandstones) from which deep groundwater is under sufficient hydrostatic and lithostatic pressure to reach the surface. This is evidenced by the SOEKOR wells that produced saline thermal groundwater from depth, as well as the KARIN borehole KZF-1. An area of **moderate vulnerability** between the southern limit of dolerite intrusions and northern limit of Cape Supergroup floor rocks, representing the Cape Basin. The presence of especially dolerite sills are likely to impede the upward migration of gas, groundwater and contaminants as evidenced by gas strikes encountered at the base of thick sills during exploration/water borehole drilling. An area of **low vulnerability** north of the Cape Basin that is characterised by a shallower target shale gas reservoir, a multitude of dolerite intrusions and a generally hotter and drier climate especially in the western portion.

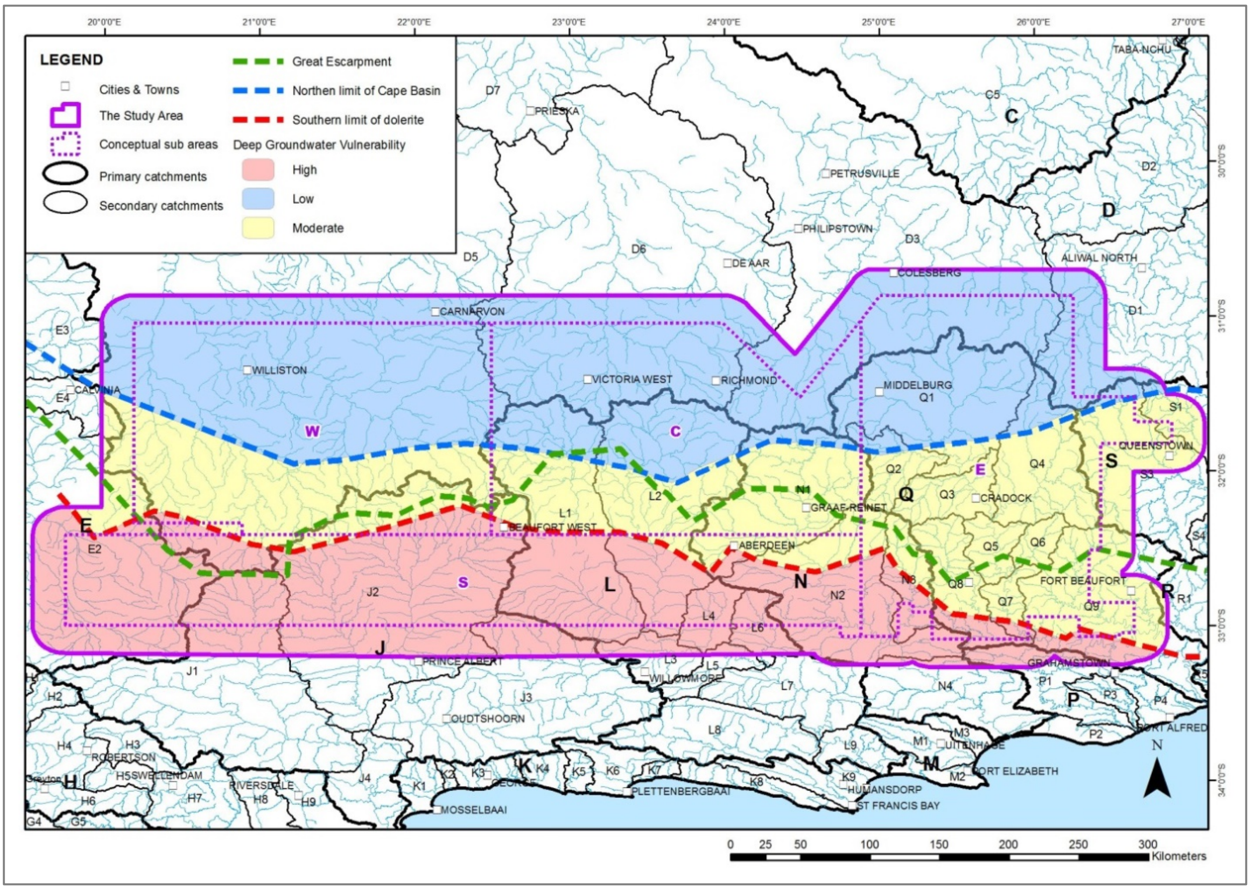

Figure 5.6: Intermediate and deep groundwater vulnerability rating (Rosewarne, 2015).

5.2.3 Surface water

5.2.3.1 <u>Occurrence</u>

The study area extends over portions of nine Primary catchments, of which the greatest areas comprise Primary catchments D (lower Orange River), J (Gouritz River), L (Gamtoos River), N (Sundays River) and Q (Great Fish River) (Figure 5.7). Relatively minor portions of the study area are drained by Primary catchments E (Olifants River) in the west, and R and S in the east (Keiskamma and Groot Kei rivers, respectively). The water resources of South Africa's Primary catchments are managed by the DWS in respect of nine Water Management Areas (WMAs), each of which is intended to be managed by a Catchment Management Authority (CMA). Not all CMAs have yet been established, but are included in the National Water Resources Strategy (NWRS, 2013), and are referred to in this Chapter as is relevant. Catchment D falls within the Orange WMA, catchment J in the Breede-Gouritz WMA (where a CMA has been established), and the remaining catchments L, N, P, Q, R and S all within the large Mzimvubu-Tsitsikamma WMA (where establishment of a CMA is imminent) (Figure 5.7).

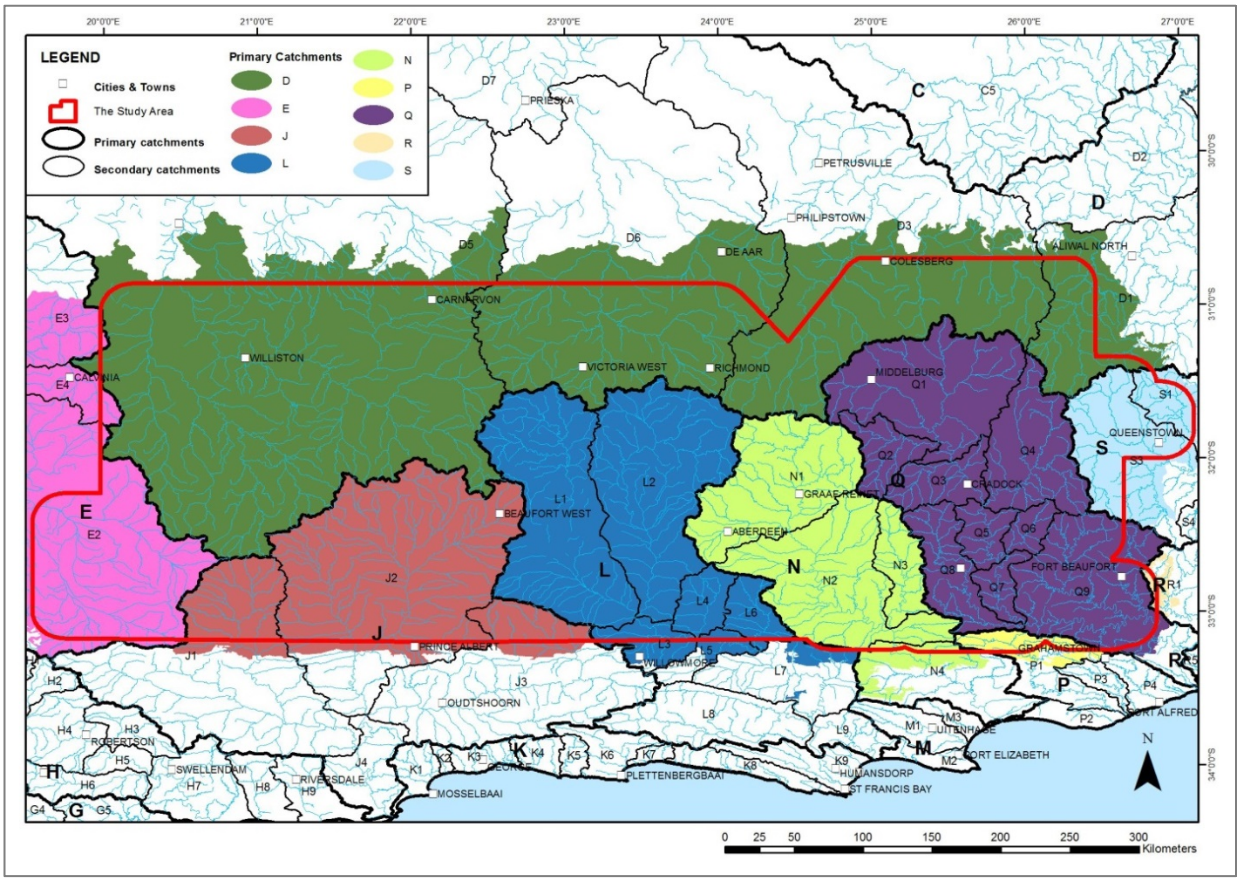

Figure 5.7: Catchment context of the study area, with Primary and Secondary catchments and Water Management Areas (WMAs) indicated: river data from Nel et al. (2011).

> ***Primary catchment:*** *The physical catchment area completely separated from other Primary catchments by watershed boundaries. DWS notation denotes Primary catchments as letters (A, B, C etc.) and Secondary catchments as numbers (e.g. A1, B5, C3 etc.)*

The Karoo is an arid area, with hydrological data modelled for Quinary catchments showing that most of the study area has an MAP of below 400 mm, with a distinct gradient of increasing MAP from the dry west (mostly <300 mm) to the east (mostly <400 mm), but with the most easterly parts of the area 400 to 600 mm and in excess of 700 mm in limited areas (refer to Figure 1.4 in Burns et al., 2016). Rainfall data (summarised in the Digital Addendum 5A – Figures 5A1.3 (A to D) illustrate a west to east gradient of increasing rainfall across the study area for data for each of the months illustrated. Rainfall is generally highest in autumn, although still <25 mm across a large proportion of the study area and <50 mm across almost all of the study area. What rainfall there is tends to be highest towards the west in winter (July) and higher in the east during the spring, summer and autumn months (Schulze, 2012). High mean potential evaporation rates at generally over 1 600 mm across the study area and in excess of 2 000 mm in the arid west (Burns et al., 2016) indicate, however, that outside of major storm events, little rainfall translates into streamflow (Figure 5.8).

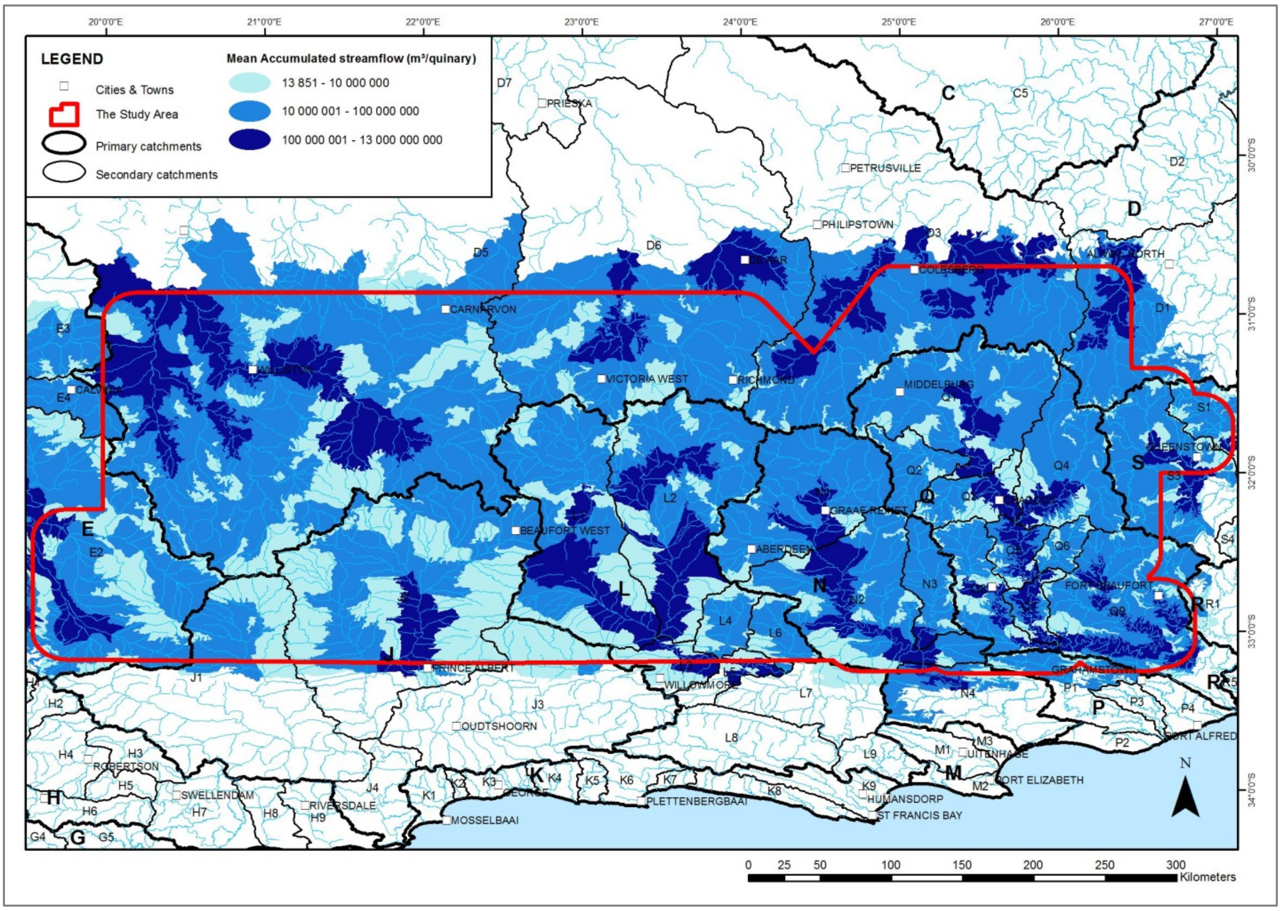

Figure 5.8: Mean annual accumulated streamflow**.** Data at quinary level. Daily runoff values were generated with the ACRU daily time-step physical-conceptual, multi-soil level and multi-purpose hydrological model (Schulze, 1995 and updates). Streamflow at Quinary exit is the runoff generated within that specific Quinary plus the accumulated runoff of all upstream Quinaries. Note that from the darker coloration one can clearly see how, for the bigger rivers, the streamflow gets larger and larger as one cascades downstream. Original data source Schulze (2012).

Rainfall is also more erratic in the south-western and central portions of the study area, as shown by high coefficients of variation (CV) in both annual precipitation (Figure 5.1) and annual accumulated streamflow (Figure 5.9). Hydrologic simulations performed as part of the scientific assessment indicate that the western/south-western portions of the study area are more prone to extreme but erratic rainfall and associated floods with high ratios of 1:10 to 1:50 year return interval for three and one day rainfall events respectively (Addendum 5A: Figures 5A1.16 to 5A1.26). In the study area the differences in flows between wet and dry years is vast, indicative of the high variability of streamflows and thus high uncertainty of assured supplies of water from local surface water sources. This amplification of variability between rainfall and streamflow (that is, an already erratic rainfall translates into greater extremes of high and low flows as a result of (*inter alia*) high potential evaporation rates) is typical of semi-arid regions (Schulze, 2012) (Figure 5.9). These extremes of high flow are further illustrated in Figure 5.11 and 5.12.

Furthermore, Figure 5.12 depicts the ratio of the 1:50 to 1:10 year extreme 3-day streamflow events. This ratio identifies areas that are particularly vulnerable to such events, with a high ratio of the very rare event to the less rare event indicating periodic "shock" events. The highest ratios are in the south-west of the study area. These data have relevance to the SGD assessment, in that the location of such activities in areas identified as of high risk in terms of severe but rare storm events would be potentially problematic from both the perspective of the resource and the development itself.

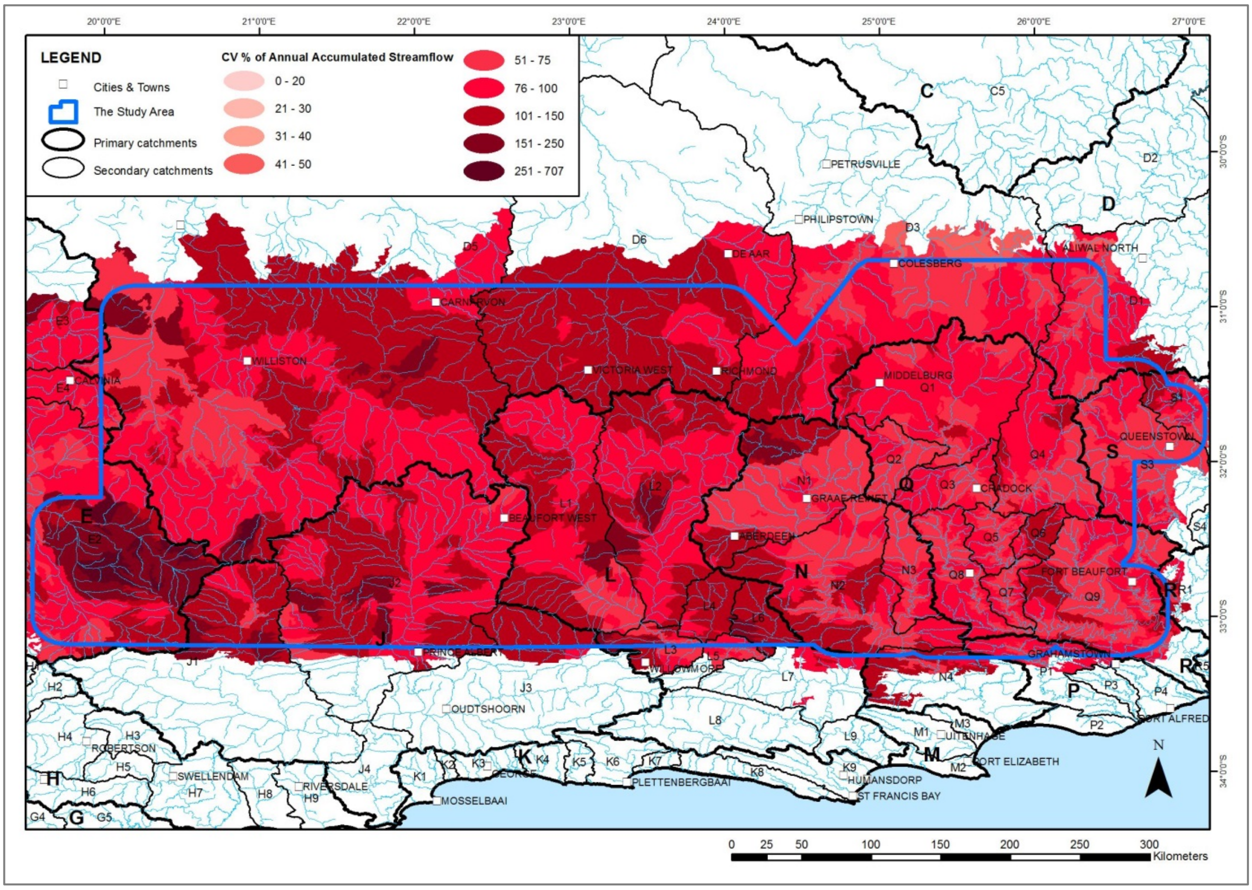

Figure 5.9: Coefficient of variation (CV) of annual accumulated streamflows CVs in the range 50–250% show high inter-annual variability in streamflows. Original data source Schulze (2012).

Figure 5.10: Spate conditions in the ephemeral (seasonal) Theekloof River north-east of Beaufort West in January 2016 (photo courtesy D. Hohne, source unknown).

Figure 5.11: Aerial view showing wide spread of flows in the episodic Renoster River in the north-western part of the study area (Orange River WMA) in April 2016 (photo courtesy D. van Rooyen).

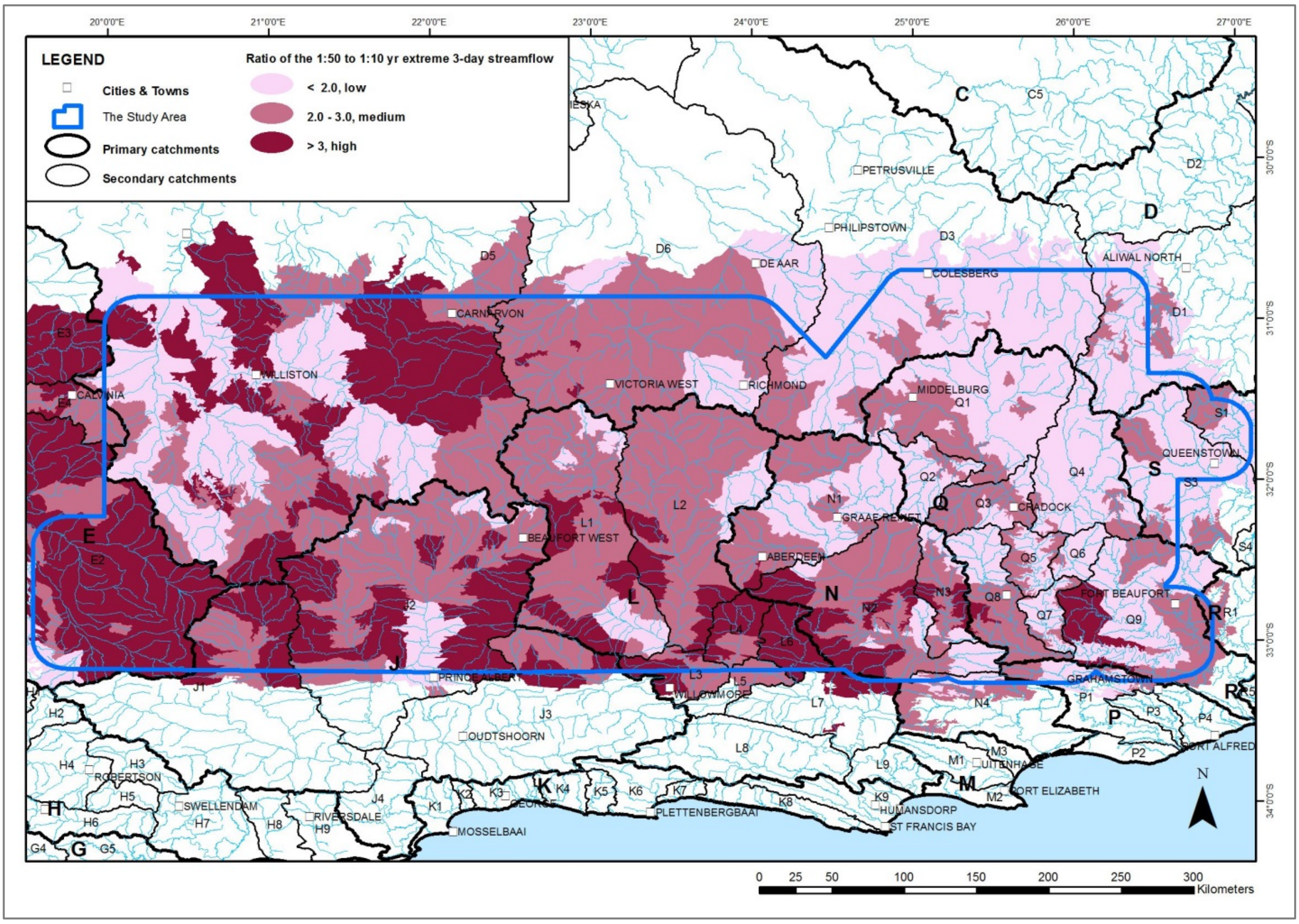

Figure 5.12: Ratio of the 1:50 to 1:10 year extreme 3 day streamflow. These data indicate areas prone to rare but highly damaging floods. Original data source Schulze (2012).

The area is also prone to drought, and the implications of a ‘severe drought’ (Burns et al., 2016) are that around 60% of the study area would receive less than 100 mm in such a year, indicative of the harsh climatic conditions existing in this region. This has a bearing on the importance of the availability of water resources to “buffer” existing users through periods of extreme drought. The World Wide Fund for Nature (WWF, 2015) note that while currently under-utilised farm dams, for example, may seem to present a possible water supply for activities such as shale gas exploration and production, these resources, where they exist, are often a critical buffer during drought. Mean accumulated streamflow volumes [which take account of the effect of evaporation and infiltration on mean annual runoff (MAR)] also generally increase toward the east (Figure 5.8), and SSI (2012) present hydrographs that show zero flows over most months of the year for selected quaternaries in the western area.

These aspects explain the fact that many of the rivers in the study area are seasonal (ephemeral) or episodic, with Quinary catchments dominated by perennial flow largely being restricted to the

Classifying river flow types:
Perennial rivers flow 11 to 12 months/year;
Ephemeral (or seasonal) rivers flow usually 3 to 10 months/year;
Episodic rivers flow less than two months per year, and sometimes not at all.

eastern part of the study area and along high mountain areas extending through the central zone of the site (along the Great Escarpment) and to the west. Extensive areas of only episodic flow occur particularly in the central, north and south of the site (Figure 5.13).

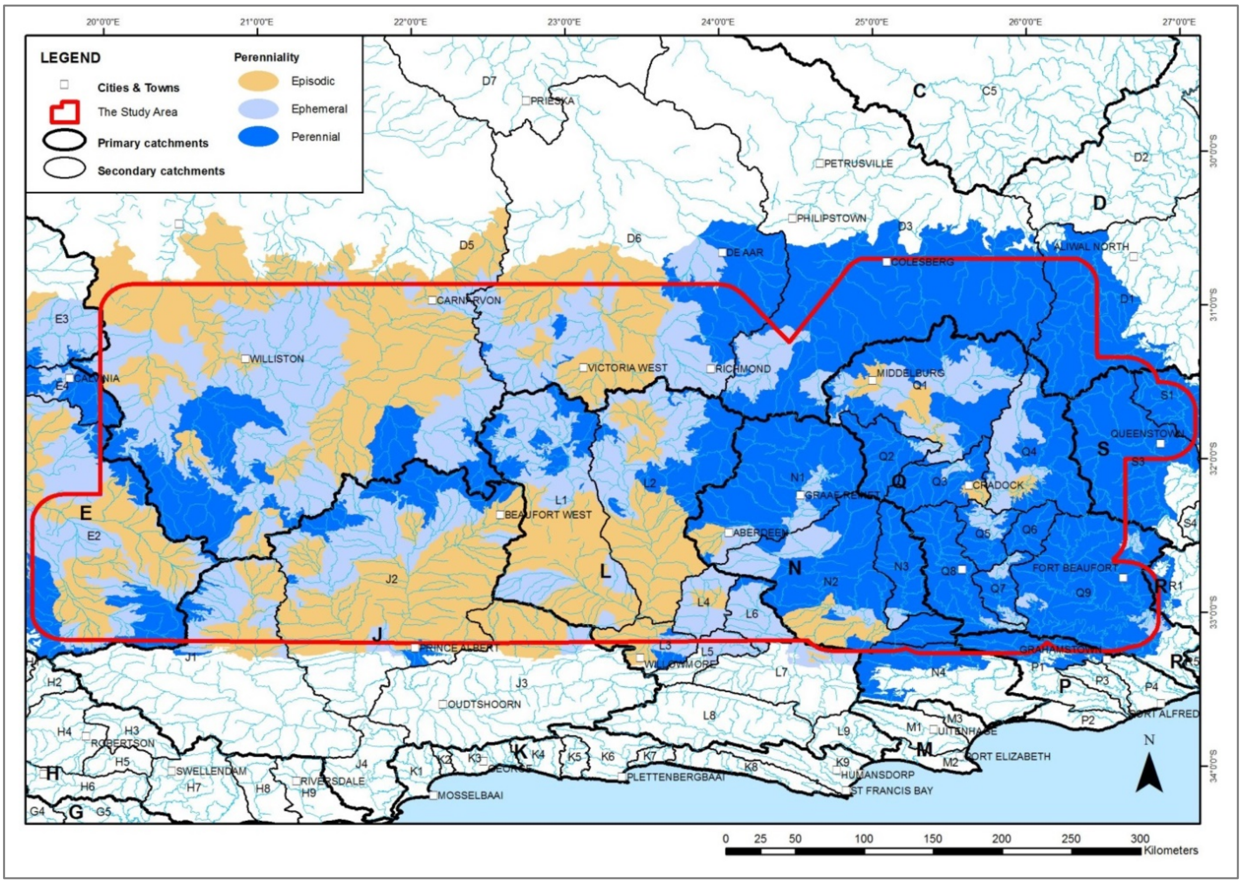

Figure 5.13: Areas of perennial, ephemeral (or seasonal) and episodic flows. Data shown as effective runoff (i.e. runoff generated minus channel flow losses to evaporation) from individual Quinaries. Information source new unpublished research by Schulze and Schütte (2016).

The low levels of perenniality in rivers in the study area, relative to those at a national level, are indicated in Figure 5.14. The significance of these from a scientific assessment perspective is that they do not provide an assured source of water for activities associated with proposed shale gas exploration to production activities, but do provide potential surface conveyance pathways through the study area for pollutants.

5.2.3.2 Water quality

The region of the Karoo under investigation is arid, and more so in the west than in the east. Very few major rivers traverse the area, and most of these are seasonal or ephemeral. The few data sets from the DWS database[1] show that the rivers are low in dissolved solids in their headwaters (within high-lying areas), becoming more saline further downstream, and that surface waters are more saline in the west of the region than in the east. High salinity values (e.g. a median conductivity of 504 mS/m in the Sak River at Williston Commonage, 1973-1988: DWS water chemistry database) in some of these systems

[1] DWS database available at: https://www.dwa.gov.za/iwqs/wms/data/000key.asp

are natural (Basson and Rossouw, 2003). Others have become more saline over time as a result of evaporative concentration of slightly saline irrigation water (Van Rensburg et al., 2011). In the Groot Vis River catchment for example (Figure 5.5), high natural salinity in rivers such as the Groot Brak River is artificially reduced for agricultural and other uses by dilution with inter-catchment transfers of fresher water from the Orange River (Basson and Rossouw, 2003; see Section 5.3).

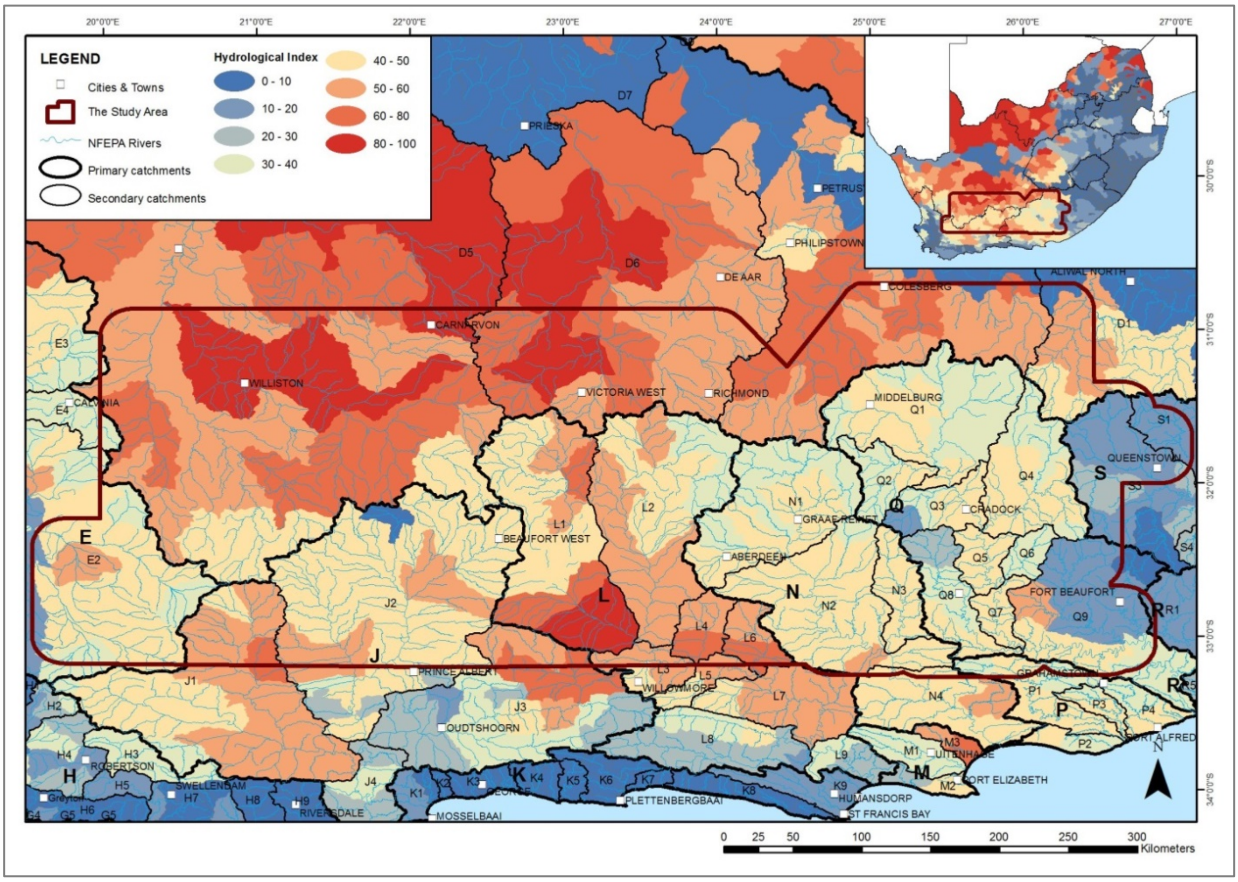

Figure 5.14: Hydrological Index (HI) data**.** Assessment of the study area in a national context, using the hydrological index (HI) of Hughes and Munster (1993) to highlight differences in flow regime through consideration of flow variability and the strength of base flow; strongly perennial systems have a low HI and ephemeral systems a low HI. [unlike the Quinary-level data shown in Figure 5.12, HI data are based on Quaternary catchments.]

Although the rivers in the study area are mainly dry, under high flow or flood conditions, large volumes of sediment can be mobilised both from the surrounding catchment and the river channels and floodplains themselves, and transported downstream in turbid flows (Basson and Rossouw, 2003a; 2003b). Although this is a natural characteristic of much of the Karoo region, it is exacerbated by poor land use practices (e.g. overgrazing, disturbance to river corridors and their floodplains, inadequately sized culverts and bridges), leading to erosion in large flow events. In-channel dams are thus prone to sedimentation, and associated loss in dam capacity. Boardman and Foster (2011) for example estimate a rate of sediment input into the Nqweba Dam on the Sundays River, near Graaff-Reinet, of approximately 1 million m^3 per year and note that in this area almost 50% of small dams are fully silted up.

The sparse population across most of the study area means that sources of pollution into surface waters are generally limited and mainly comprise waste water discharges. The DWS water quality database[2] indicates that of the fifteen waste water treatment works (WWTW's) shown in the study area, four discharge directly into rivers in the study area and three discharge variously into the Orange River and Gariep Dam to the north of the study area (Table 5.2).

Table 5.2: Disposal of effluent from waste water treatment works in the study area

Name of works	Primary catchment	Manner of effluent disposal
Beaufort West	J2	Kuilsrivier – tributary of the Gamka River
Aberdeen	N1	Irrigation
Graaff- Reinet	N1	Sundays River
Grootfontein College of Agriculture	Q1	Irrigation
Middelburg	Q1	Tributary of the Klein Brak River
Burgersdorp	D1	Unspecified – assumed to be irrigation
Somerset East	Q5	Irrigation
Venterstad	D3	Orange River
Oviston	D3	Gariep Dam
Van der Kloof	D3	Gariep Dam
Nou Poort	D3	Unspecified – assumed to be irrigation
Zastron	D3	Unspecified – assumed to be irrigation
Tarkastad	Q4	Irrigation
Bedford	Q7	Irrigation
Adelaide	Q9	Koonap River

Effluent from the other WWTW's is used in irrigation, and is likely to contribute nutrients and other pollutants from this source into rivers as diffuse runoff from these areas. These effluent discharges convey loads of nutrient enriched water into these systems, with phosphorus and nitrogen nutrients usually considered of most concern from a water quality perspective, along with bacterial contamination and the effects of low oxygen as a result of decomposition of high organic loads. Effluent from the remaining WWTW's is used in irrigation, and is likely to contribute nutrients and other pollutants from this source into rivers or groundwater respectively as diffuse surface flows following rains and/or through infiltration to shallow aquifers.

Pollution of episodic and ephemeral river systems or their catchments can be highly problematic. Continuous discharges of effluent, for example, may for a large proportion of the year constitute the full flow of water in the river, rendered more concentrated by high rates of evaporation. Episodic contamination of these rivers or their catchment areas may also be of great concern, as intermittent flows may result in extended residence times for pollutants in isolated pools which, in perennial systems, would often be able to move "plugs" of pollution downstream.

Apart from the above localised and mainly point source impacts, water quality in rivers in the study area is not considered highly impacted and the State of the Rivers Report for the Gouritz WMA (River Health Programme (RHP), 2007) allocated 'Good' to 'Natural' water quality scores to assessed rivers in the study area (albeit limited to only five monitoring sites that fell within the study area).

[2] DWS water quality database available at: https://www.dwa.gov.za/iwqs/wms/data

Groundwater in the region daylights in several areas as springs (known locally as "eyes") some of which produce hot water, indicating that they are produced at substantial depths (Murray et al., 2015). Their water chemistry is expected to reflect that of the deep aquifers from where they rise (Subsection 5.2.2.2).

5.2.3.3 Aquatic ecosystems

The aquatic ecosystems in the study area reflect their particular hydrological, climatological and geological conditions within this area, and comprise natural rivers, wetlands and springs and artificial features such as in- and off-channel impoundments (dams). Chapter 7 of the scientific assessment, by Holness et al. (2016) describes the biodiversity aspects of these systems. The present Chapter focuses on their roles in the hydrological cycle, where they function both as ecosystem drivers and as conduits between surface and groundwater systems (vertical linkages) and between the activities in any particular part of the study area and downstream receiving areas.

> ***Watercourses** and **wetlands** are defined in this study as per the following definitions of the National Water Act (NWA) (RSA, 1998a):*
> ***"watercourse"** means -*
> *(a) a river or spring;*
> *(b) a natural channel in which water flows regularly or intermittently;*
> *(c) a wetland, lake or dam into which, or from which, water flows; and*
> *(d) any collection of water which the Minister may, by notice in the Gazette, declare to be watercourse, and a reference to a watercourse includes, where relevant, its bed and banks;*
> ***"wetland"** means -*
> *land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil.*

Figure 5.15 shows the spatial distribution and mapped extent of known watercourses (rivers and wetlands) and other wetland types (i.e. those not associated with channelled inflow) in the study area, with rivers mapped at a scale of 1:500 000, based on river and wetland data from the National Freshwater Ecosystem Priority Area (NFEPA) data (Nel et al., 2011), but including an updated wetland layer developed by Holness et al. (2016).

Many of the riverbeds in Karoo valleys are sandy, reflecting both alluvial and aeolian deposits, and support primary aquifers (Colvin et al., 2007), with water sometimes occurring in these river beds primarily below the surface. Figure 5.15 shows extensive areas of sandy river bed features ("dry rivers") in parts of the study area, as mapped by Holness et al. (2016). For intermittent rivers in the Karoo, Colvin et al. (2007) refer to the classification of Vegter and Pitman (1996) that considers both surface and groundwater contributions to flow, describing how short-term (intermittent) discharges into such watercourses occur when the primary aquifer intersects with the river channel, driven by groundwater recharge through precipitation at higher elevations (Colvin et al., 2007). During dry periods, groundwater storage is depleted by such effluent, exacerbated by evapotranspiration and evaporation. Surface flow in the rivers from local stormwater runoff may also discharge into the primary aquifer, locally replenishing groundwater (Colvin et al., 2007). Streams in the Karoo, such as the upper reaches of the Salt River (Beaufort West), the Kamdeboo, Sundays and Brak Rivers (De Aar) are cited by Colvin et al. (2007) (after Vegter and Pitman, 1996) as examples of this kind of system.

> ***Aquifer dependent ecosystems (ADE's)*** *are ecosystems that depend on groundwater in or discharging from, an aquifer (Colvin et al., 2007). They may occur where groundwater discharges from an aquifer to the surface, forming aquatic features such as springs or wetland seeps, or where aquifers contribute to the baseflow of rivers.*

The wetlands indicated in Figure 5.15 comprise valley bottom wetlands along river channels, seeps, and by far the most dominant wetland type; pans (see Holness et al., 2016). The latter are for the most part shallow depressions in the landscape in many cases connected to highly ephemeral systems only, which overtop into the pans, leaving them to dry out slowly through the combined effects of infiltration and evaporation. These features often represent aquifer dependent ecosystems (ADE's) in the landscape. The largest of these pans include the Grootvloer-Verneukpan complex, which plays an important role during migrations of biota, enabling them to have access to breeding grounds in the upper reaches of the Sak River (Esterhuizen et al., 2014). Verneukpan and Grootvloerpan (both located just north of the study area, along the Sak River, reach depths of up to 1.2 m during wet periods, though this happens rarely (Thieme et al., 2005), with Baard et al. (1985) noting that Verneukpan contained substantial water only five times during the period from 1885 to 1985 (Baard et al., 1985). Within the study area itself, Swartkolkvloer and Blombergsevloer form part of the same extended system of pans along the Sak River (Mucina and Rutherford, 2006).

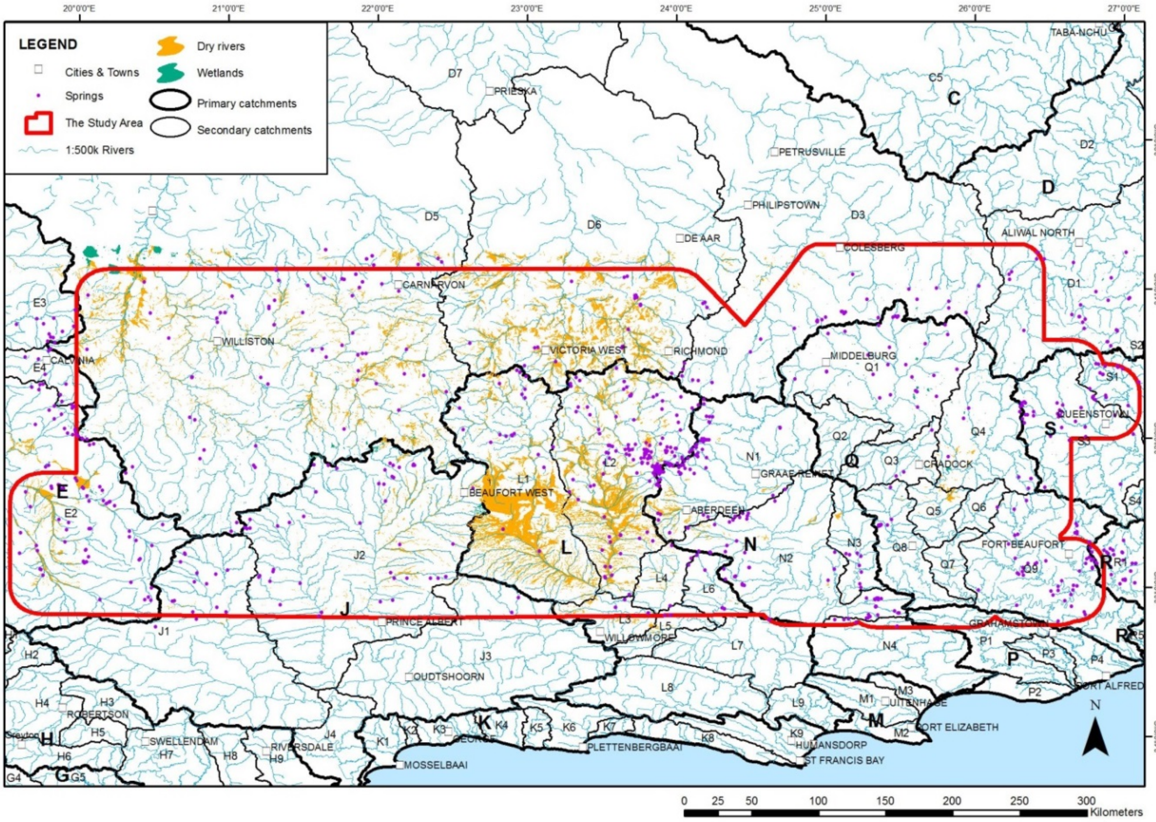

Figure 5.15: Natural and artificial river and wetland extent. Figure based on NFEPA river and wetland data (Nel et al., 2015) with "dry rivers" added as a layer for the scientific assessment (Holness et al., 2016) and with DWS Primary and Secondary catchments shown.

From a hydrological perspective, such pans provide localised attenuation and storage of runoff. Their value as a water resource for local populations is however usually low, due to their characteristically high salinities, as a result of the high rates of evaporative concentration in the region, particularly with distance west and north. To a degree, the pans thus also accumulate chemically stable nutrients, salts and other constituents carried into them by surface runoff. Transport of these substances out of the pans occurs either by wind action on dry pans or, in the case of those linked to channels, during flood events.

While pans usually are associated with flatter portions of the study area, where drainage lines overtop and flood broad depressions, non-thermal springs and wetland seeps are associated with Karoo dolerite dykes and sills. These wetlands are typically situated at the base of dolerite cliffs or on dolerite slopes, in depressions along fractures or topographical breaks, and are fed by groundwater seeping from deep, fractured aquifers or unconfined alluvial aquifers (Nhleko, 2003). They are one of five types of secondary aquifer associated with ADE's recognised in South Africa (Colvin et al., 2009). Colvin et al. (2007) note that the most hydrogeologically vulnerable ecosystems are the seeps occurring on the lower slopes, which depend on spring discharges from the upper unconfined aquifer. In the event that activities such as upslope abstraction occurs; drawing down the aquifer water level, these systems would be highly affected. The distribution of springs in the study area is shown separately as unscaled spot points in Figure 5.16, and these reflect direct links to groundwater.

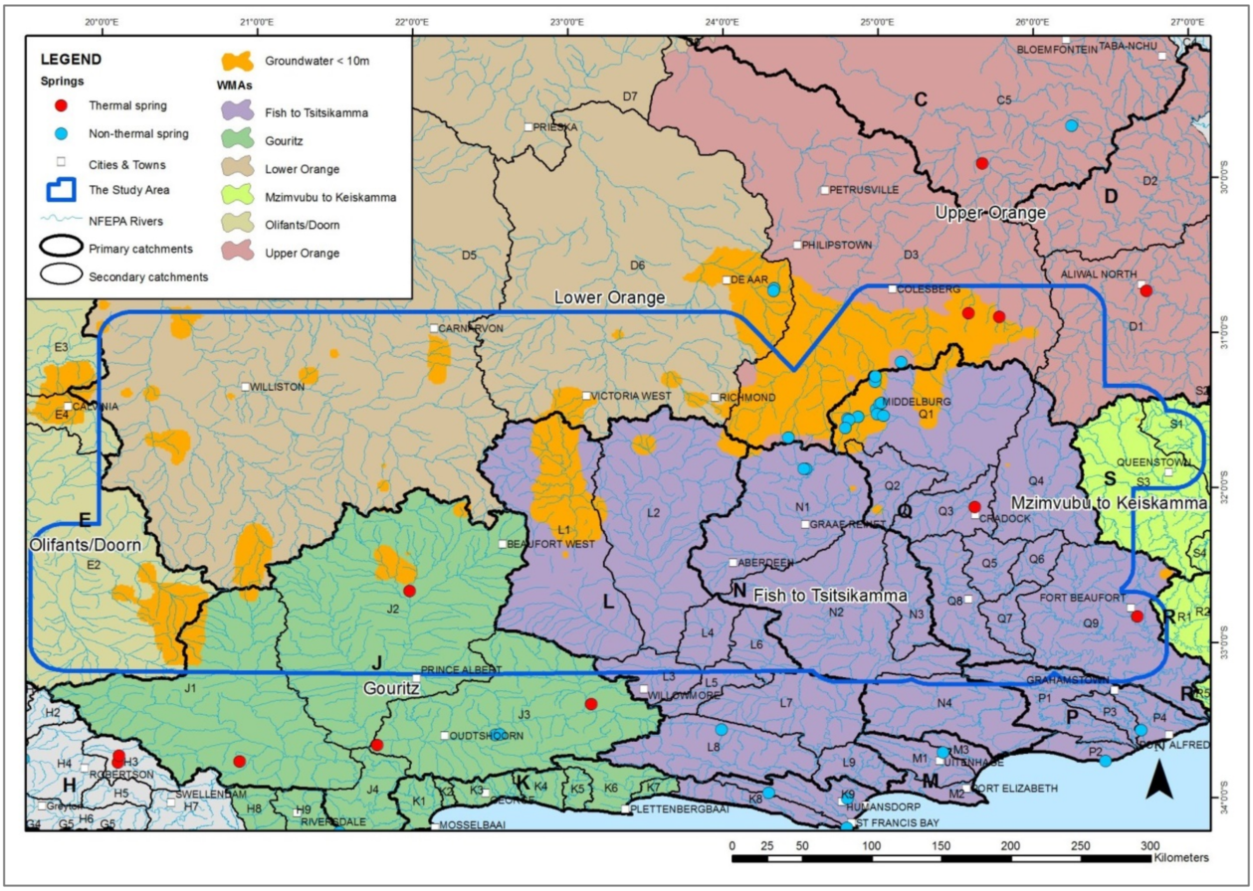

Figure 5.16: Location of known cool and warm/thermal springs in and around the study area. The figure also indicates where groundwater is expected to be shallow (<10 m below surface); data from DWA (2005). Note that springs are shown as unscaled points and not spatially representative polygons.

Watercourses downstream and at the outlet of springs are considered at least partially groundwater-dependent. In this scientific assessment, the potential for groundwater-dependent ecosystems (GDE's) associated with shallow aquifers is considered to include areas where groundwater lies within 10 m of the surface, and is presented in subsequent sections of this Chapter. Note that this assumption is conservative, with Colvin et al. (2007) classifying groundwater-dependent wetlands on the basis of depth-to-groundwater of <5 m. The amendment to <10 m takes cognisance of uncertainties regarding the actual spatial extent of groundwater/surface ecosystem interactions, and thus the need for a precautionary approach in the present study, as well as the fact that Colvin et al. (2007) used the presence of groundwater <30 m as shown by hydrocensus data as a coarse estimate of possible groundwater dependent ecosystems. Most of the non-thermal springs shown in Figure 5.16 in the study area occur in areas where groundwater has been mapped at distances <10 m from the surface. The figure also reflects available data relating to the known location of springs in and around the study area, with four hot spring areas included. These ecosystems are highly dependent on groundwater.

The study area also includes numerous farm dams as well as several large impoundments (e.g. Nqweba Dam on the Sundays River, the Gamka Dam on the Gamka River and the Grassridge Dam on the Grootbrak River), which contribute to water supplies for various towns (e.g. Graaff Reinet, Beaufort West and Cradock) and agricultural users. Like natural pans, these too act as depressions in the landscape and may thus also accumulate chemically stable nutrients, salts and other constituents over time. Many of the farm dams are however fed by wind-pumped groundwater, providing a direct surface-groundwater link.

The importance of the ephemeral aquatic ecosystems of the Karoo

In contrast to perennial rivers and wetlands, surface water in the rivers and wetlands occurring in the study area are predominantly ephemeral in nature. These systems are event driven, being either dry or in flood. The onset, duration, frequency and magnitude of low and high flows are highly variable, unpredictable and mostly unknown. The variability of flows is due to low mean annual precipitation, high potential evaporation which exceeds rainfall in most of the study area, and is also dependent on land use management.

Knowledge of environmental water requirements in non-perennial rivers is still in its infancy compared to perennial rivers, and has contributed globally to the poor ecological state of these systems (Acuña et al. 2014). In South Africa, understanding of the functioning of non-perennial rivers and streams has increased markedly over the last decade (Seaman et al., 2010; 2013). These studies emphasised the important role of pools, the connectivity between them, and the interaction between surface and sub-surface water play in maintaining the ecological integrity of these rivers. Pools act as important refugia during dry periods, not only for aquatic biota and riparia, but also for other organisms associated with freshwater like amphibians, birds and small mammals during dry periods. The lack of good quality hydrological data and suitable integrative hydrological models make it very difficult to predict how these organisms, associated with the pools, will react to changes in water quantity and quality over time under non-perennial conditions. Neither is there baseline data on how these species will react to change. Furthermore, the species that occur in these rivers are generalists that are able to survive the harsh conditions, making them less sensitive to change compared with species occurring in perennial rivers. That being said, these species might become extinct by the time change is detected, as the limits of acceptable change are currently unknown.

Groundwater plays an important role in the persistence of pools after flow ceases. Understanding of surface water and groundwater interaction is mostly conceptual and needs to be tested. Rivers in the study area are all classified as groundwater dependent ecosystems (Colvin et al., 2003) from a groundwater perspective, and can be described as ecosystems that depend significantly on groundwater for their hydrological functioning. The effect that additional groundwater extraction for SGD might have on the sustainability of these rivers, is unknown and of great concern. It is possible that over-abstraction could damage these GDE's beyond repair. An added uncertainty is that recharge data is only available for localised areas, but is lacking on a regional scale. Recharge is influenced by land use changes and it is expected that the study area, because of its arid nature, will be very sensitive to a change in land use. A change in land use from natural to agriculture/industrial could result in more pronounced erosion, sedimentation, floods, less infiltration from precipitation and higher rates of evapotranspiration. This uncertainty is aggravated by the limited rainfall and poor/limited distribution of gauging stations in the study area.

The knowledge uncertainties and gaps regarding surface water systems in semi-arid to arid areas hamper the ability to manage these resources in a sustainable manner. In the light of climate change, an increasing human population and the possible impacts of SGD, it is imperative that resources for question-driven research are made available to address the attendant uncertainties.

5.2.3.4 Resource condition

Water resources in the catchments over which the study area partially extends have been classified in terms of their present ecological state (PES) as part of a national assessment, using a combination of expert knowledge, desktop assessments and ground-truthing, with PES status being determined for rivers and, to a limited extent, valley bottom wetlands (DWS, 2014).

PES data for the study area and its downstream catchments are shown in Figure 5.17. These data indicate that PES for rivers in Quaternary catchments in the study area are in their most natural condition in Primary catchments J and E, with large sections of river in a category A or B. Rivers in catchments L, N, Q, R and S tend to be in a more degraded condition, with few category A reaches and more category C and D reaches. Excluding the Orange River sub-catchments, the lower reaches (outside of the study area) are generally categorised as more impacted than the upper reaches. In addition, more (mainly main stem) rivers in the eastern third of the site are classified as PES Category D or worse than in the western two thirds. This apparent west-east gradient of increasing degradation probably reflects in part the low levels of usability of many of the rivers in these arid Karoo regions, where salinity and poor flow assurance mean that such rivers may not have been affected by impacts that degrade many less saline or perennial systems (e.g. abstraction, grazing and impoundment). Reliance on groundwater resources in many areas of the Karoo thus means that many of these surface systems remain in a near-intact condition.

Present ecological state (PES)

PES is a measure of river condition that is used to set so-called Ecological Specifications (EcoSpecs), on the basis of which the Ecological Reserve for different river reaches is calculated, and from which remaining water resources can be allocated, after accounting for the Basic Human Needs Reserve.

PES assessments assign river reaches to one of six PES categories, ranging from A to F, with A representing rivers in a natural or pristine condition and F representing rivers in a Critically Modified condition or state. PES categories of E (Seriously Modified) or F are not considered sustainable (Kleynhans et al., 2005). Since sustainable resource use is an important tenet underpinning the NWA (RSA, 1998a), aquatic ecosystems need to be managed in a condition that is above (better than) Category E. Thus the management objective for all aquatic ecosystems needs to be in an overall state that is better than Category E – that is, Category D or better.

From a resource allocation perspective, such systems are unlikely to be further affected by increased water allocation pressures, as available water is limited. With distance east, as the resource quality improves for human requirements (e.g. irrigation and domestic supply), so river condition appears to deteriorate, reflecting a reduction in natural flows. Figure 5.17 shows that many of the southern rivers downstream of the study area are already in a PES Category D, highlighting the fact that additional water resource allocations from these systems might reduce their condition to below sustainable levels. Note however that a detailed interrogation of Quaternary level PES with regard to water quantity and the effects of reduced water quality on future PES category are beyond the scope of this assessment. An example of ephemeral flow is shown in Figure 5.18.

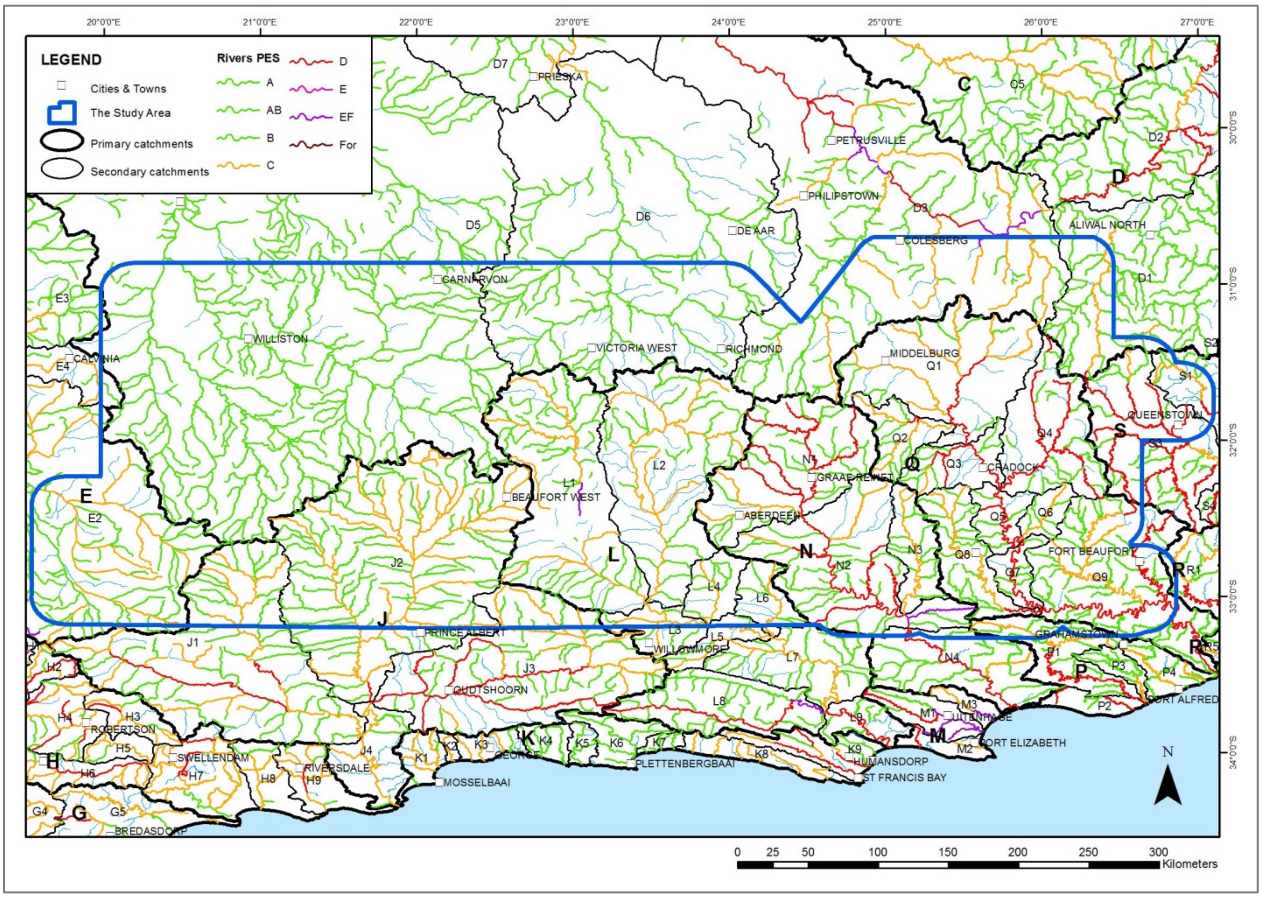

Figure 5.17: Present ecological state (PES) data for Quaternary rivers (data from DWS, 2014).

Figure 5.18: Flows in the ephemeral Vis River, April 2016 (photo courtesy D. Hohne).

5.2.4 Surface and groundwater interaction

The sporadic flow regime that characterises stream and river discharges in the Karoo environment generates a significant interaction with groundwater resources via channel transmission losses. In the majority of instances, the stream and river courses occupy channels filled with unconsolidated sediments ranging from clays and muds through fine-grained to coarse-grained sands and gravels. The extent of these alluvial deposits is often limited in depth (<10 m) and lateral extent (<100 m), but is nevertheless sufficient to serve as a reservoir to collect infiltrated water, restrict its loss to evaporation, and release it gradually to the underlying shallow aquifer. In Botswana and Namibia, such features are known as sand rivers.

The loss of groundwater to streams and rivers generates baseflow, which in the Karoo environment is very seldom perennial. The hydraulic linkage between surface water and groundwater therefore does not represent a flux where a channel transmission loss upstream is balanced by a channel transmission gain (resurgence) further downstream. Groundwater losses to streams/rivers are likely to occur mainly where springs and seeps daylight in the landscape, and include a limited number of assumed deep aquifer discharges (‘thermal springs’) and shallow aquifer outlets (springs), the known locations of which are shown in Figure 5.16. An example of seep and spring wetland features in the landscape is provided in Figure 5.19.

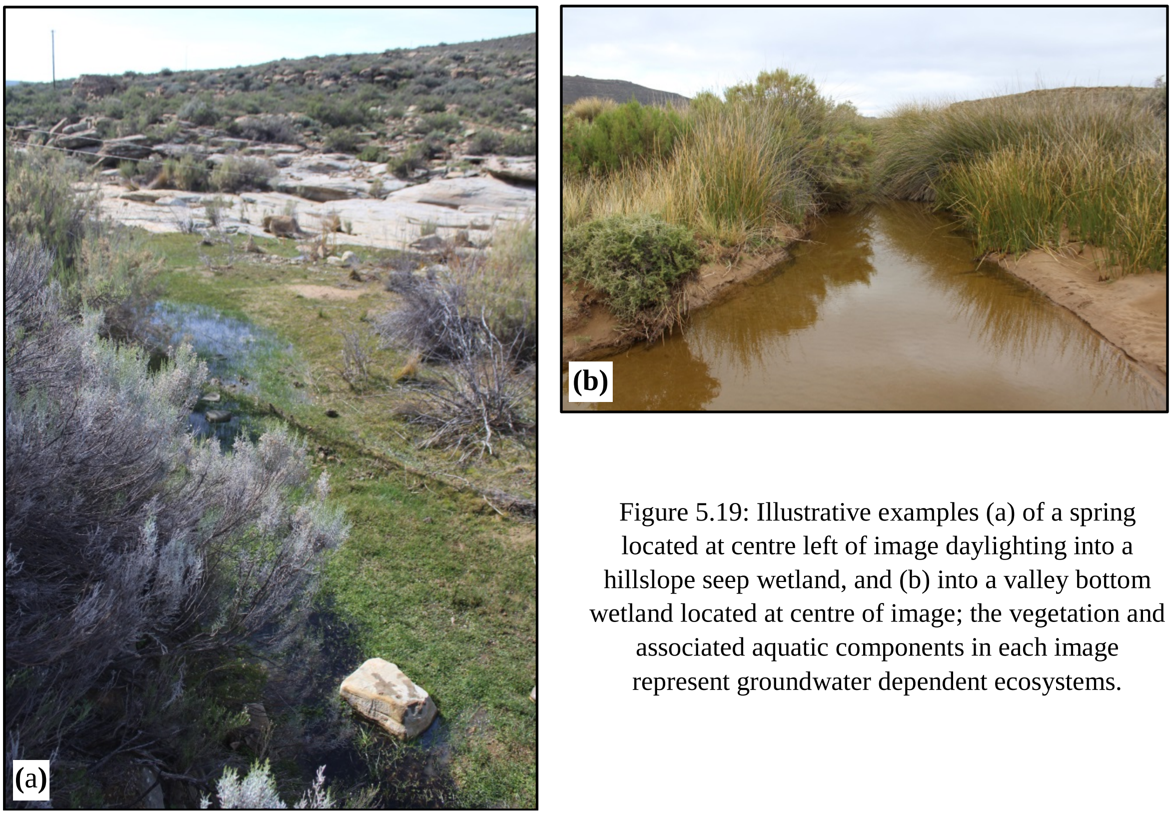

Figure 5.19: Illustrative examples (a) of a spring located at centre left of image daylighting into a hillslope seep wetland, and (b) into a valley bottom wetland located at centre of image; the vegetation and associated aquatic components in each image represent groundwater dependent ecosystems.

The study area experiences a mean annual evaporation (MAE) from open water surfaces of >1 600 mm. These circumstances and the low rainfall together have a more direct influence on surface water resources than on groundwater resources. Part of the precipitation infiltrates the sub-surface to replenish groundwater resources. This quantity varies both spatially and temporally, depending on various factors such as vegetation cover, the nature of the soil profile and underlying geologic strata, the depth to water table, and the magnitude and intensity of rainfall. Recharge is typically expressed as a percentage of MAP. Although ranging from 1 to 5%, a value of 3% is generally accepted as approaching the upper limit for ‘shallow’ aquifers typically located within 150 m of the surface in the Karoo environment (Van Tonder and Kirchner, 1990). For the purposes of SGD, the maximum depth of these resources is conservatively set at 300 m (Rosewarne and Goes, 2012; Vermeulen, 2012) to meet the precautionary principle.

Groundwater recharge might reasonably be expected to be lower in the drier western portion of the study area than in the wetter eastern portion. In quantitative terms, 3% recharge from 300 mm of rainfall is equivalent to 9 000 m^3 per square kilometre per annum ($m^3/km^2/a$), or 90 m^3/a per hectare. In the context of livestock watering, a requirement of 5 L/d/LSU (litres per day per large stock unit) means that recharge on 1 ha can water ~50 adult sheep per year. At a carrying capacity of 7 ha/LSU (Du Toit, 2002), this would require 350 ha of grazing veld to capture 31 500 m^3/a of recharge. These indicative values will vary considerably across the study area depending on differences in climate and physiography, which complicates recommendations for the sustainable abstraction and management of groundwater resources.

Artificial recharge (AR) of aquifers has been successfully used at a number of sites in South Africa, most notably at Atlantis on the West Coast for the past 30 years (DWA, 2010). Artificial recharge is a very attractive option to maximise the value of groundwater resources. Within the study area, AR is practiced at Williston, and the DWS intends developing an AR scheme at Saaipoort located 10 km from Carnarvon and 70 km from Vanwyksvlei to supply both these towns with groundwater (Fourie et al., 2016) in the coming year (2017). Artificial recharge areas are defined differently to natural recharge areas, although parts of the former could overlap with the latter in shallow aquifer areas. Natural recharge of deep confined aquifers often occurs at distal and elevated locations many kilometres or more from where these aquifers might be tapped by a borehole. Artificial recharge of these systems might be similarly accomplished.

5.3 Water resources

5.3.1 Availability and demand

Water demand for SGD involves both the direct operational requirements for gas extraction as well as the ancillary requirements for infrastructural developments to support shale gas operations. The most obvious of these include infrastructural developments such as road construction and wellpad construction.

One of the key indirect demands on water resources that is often overlooked is the increased requirements for domestic use associated with the local influx of people to support the industry either directly or indirectly. Whereas water resources for the operation itself may be sourced from seawater or boreholes that produce low quality groundwater, increased domestic demands for potable water are an important consideration, particularly in the Karoo, an area that is currently sparsely populated, largely due to water scarcity.

For the purpose of this scientific assessment, water availability was evaluated by determining the ratio of current water use to water supply at a Quaternary catchment level. This calculation essentially provides an index of water scarcity that describes the surplus (or deficit) of water available for further development. In the case of surface water resources, nearly half of the Quaternary catchments are in deficit indicating no surplus for further development. (i.e. WSI >100%; Figure 5.20). Catchments with the greatest stress are those draining the Fish River within the Mzimvubu-Tsitsikamma WMA (Figure 5.7). Although Figure 5.20 indicates some water resource availability in the study area (mainly in the Orange WMA); these figures do not take into consideration the requirements for meeting the Ecological Reserve. Indeed, in their study of Water Resources Availability and Utilisation at the WMA, the DWA (2003) found that once existing users had been accommodated, and the requirements for meeting the Ecological Reserve had been met, there was no surplus water in the Orange WMA where water requirements already exceeded available supply (and where NWRS (2013) note that the ecological Reserve is not being fully met either). In the (then) Fish-to-Tsitsikamma WMA, surface waters had already been highly developed with limited potential for further development, and with requirements for urban and irrigation use expected to rise from the time of the DWA (2003) study to 2015 (summarised by SSI, 2012). In 2003, water resources in the Sundays River were already fully developed with no excess availability, while small volumes remained available after accounting for existing requirements in the Gamtoos and Great Fish catchments.

Index of Water scarcity (WSI): *a measure of water stress in a catchment where water use is expressed a percentage of water available as follows:*

$$For\ Surface\ Water: \frac{Water\ Use}{(nMAR)}$$

$$For\ Ground\ Water: \frac{Water\ Use}{(GW\ recharge)}$$

Where:

Water Use *includes the total annual water withdrawals (municipal, industrial and agricultural).* ***nMAR*** *is the naturalised mean annual runoff taken from the WR2012 dataset; GW recharge = groundwater recharge taken from the GRAII dataset.*

The ***Ecological Reserve*** *is defined in the National Water Act (Act 36 of 1998) as "… the quantity and quality of water required … to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource".*

Based on registered groundwater use provided in the Water Authorisation Management System (WARMS) database, ~35% of Quaternary catchments (particularly those within the Breede-Gouritz WMA and the western extent of the Mzimvubu- Tsitsikamma WMA) are currently over-utilised and thus represent extreme groundwater stress (Figure 5.19). Unlike surface water resources, >50% of the catchments within the study area utilise <25% of available groundwater (Figure 5.21), suggesting that groundwater resources within the study area offer a surplus for development. However, water use from the WARMS database is based on registered water use. In most instances municipal groundwater use is unlicensed and unquantified, despite ~20 towns in the study area being totally dependent on groundwater for municipal supply, and a further 14 relying in part on this resource. Furthermore, Schedule 1 use for reasonable domestic, gardening and stock watering purposes is not licensable. Cumulatively, such use probably represents a substantial volume.

Combined groundwater and surface water scarcity for each catchment is given in Figure 5.22. This spatial expression of water resource stress emphasises the deficit of either surface or groundwater resources throughout the study area. Collectively, the most water stressed catchments include those within the northern region of the Breede-Gouritz WMA, the south western extent of the Mzimvubu-Tsitsikamma WMA as well as the drainage area for the Great Fish River (Figure 5.22).

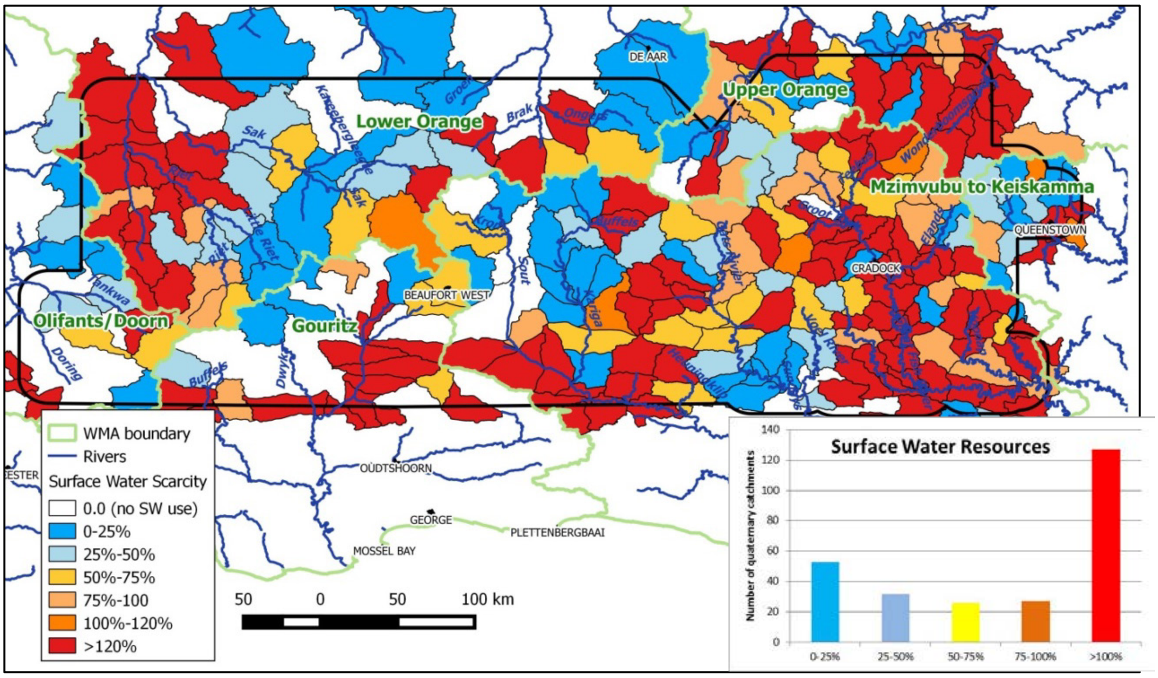

Figure 5.20: Water scarcity as an indicator of water stress at a Quaternary catchment scale for surface water resources. Catchments with a value ≥100% are those where the resource is either fully utilised or in deficit. Note that WARMS data exclude Schedule 1 Water Uses in terms of the National Water Act (NWA), and the figures shown here are thus conservative (i.e. they overstate resource availability).

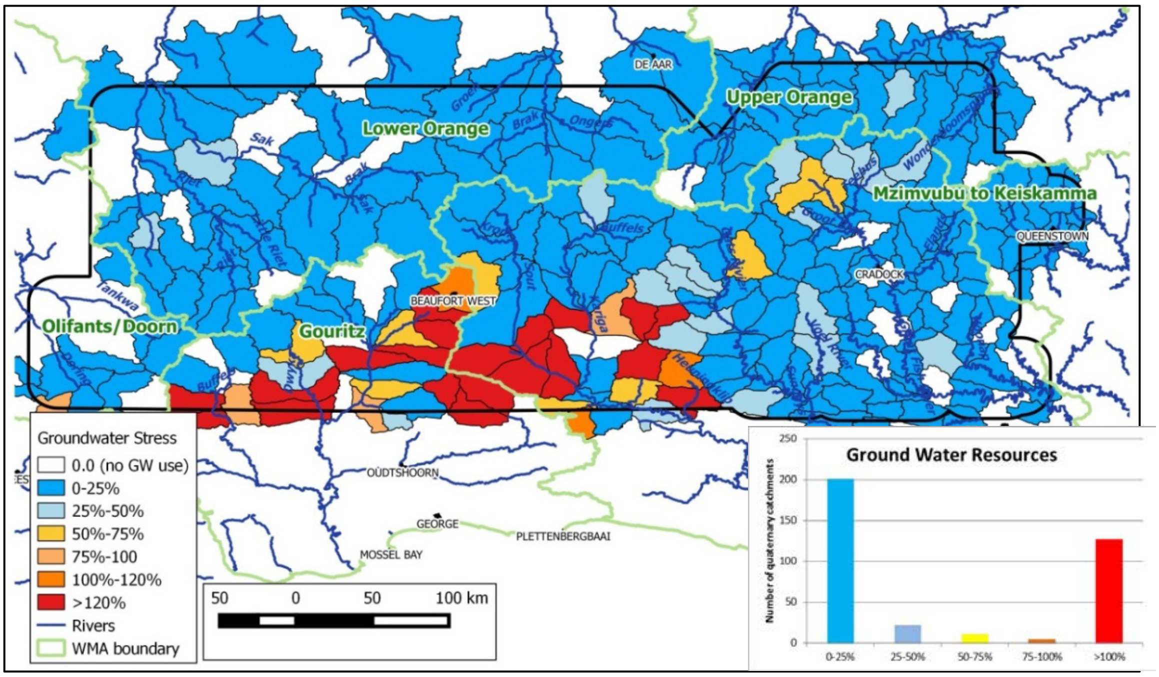

Figure 5.21: Water scarcity as an indicator of water stress at a Quaternary catchment scale for groundwater resources. Catchments with a value ≥100% are as for Figure 5.20. The bar graph summarises water use per WMA. Note that WARMS data exclude Schedule 1 Water Uses in terms of the NWA, and the figures shown here are thus conservative (i.e. they overstate resource availability).

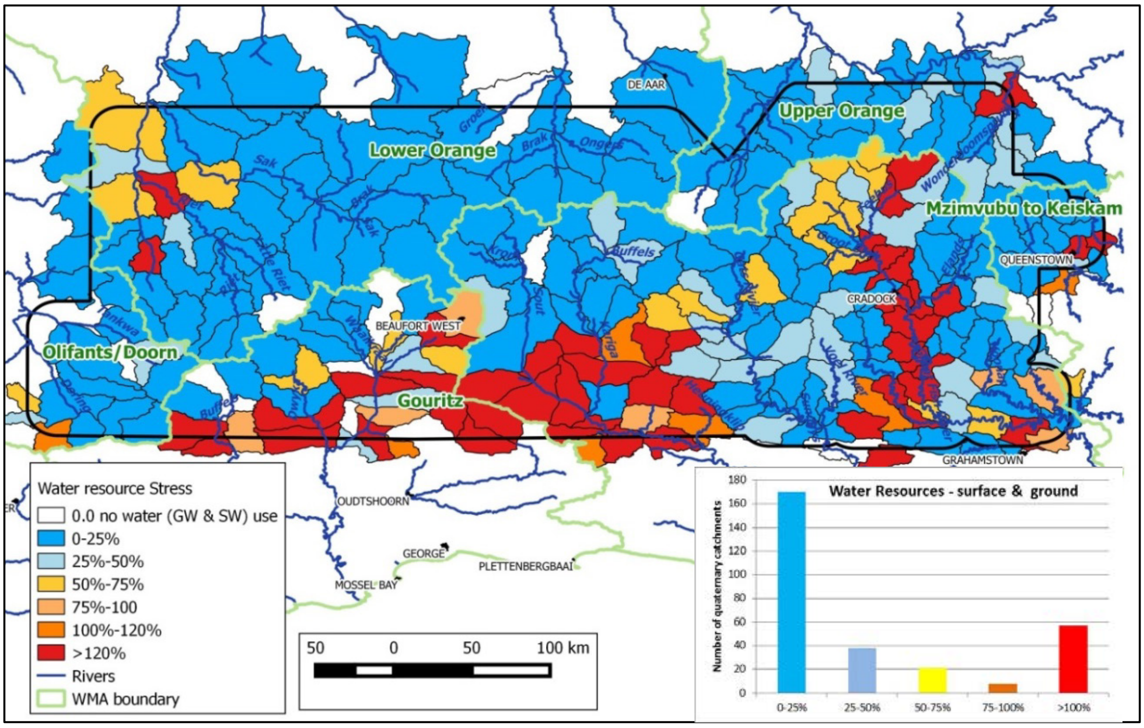

Figure 5.22: Water scarcity as in indicator of water stress at a Quaternary catchment scale for both surface and groundwater resources. Catchments with a value ≥100% are as for Figure 5.20. The bar graph summarises water use per WMA. Note that WARMS data exclude Schedule 1 Water Uses in terms of the NWA, and the figures shown here are thus conservative (i.e. they <u>overstate</u> resource availability).

Besides the water stress situation presented in Figure 5.21 to 5.23, the "All Towns" dataset developed as part of the DWS's water reconciliation strategy undertaken at a national scale, provides an indication of water availability for towns, villages and clusters of villages, together with a projection of the water shortage situation over the next 10 years (Figure 5.23). Although the data used in this assessment was based on 2008 data, these data provide a useful indication of those towns or settlements which are most vulnerable to water shortages should further demand increase. While these data suggest that there are no predicted shortages in the Orange WMA, water resources in the other two main WMA's considered in this scientific assessment are either in deficit already, or water shortages are expected in the near future. These assessments do not, moreover, take into account the projected decreases in streamflow in large parts of the study area, as described in Section 5.3.3.

On the basis of the above, it is apparent that additional surface water resources are unlikely to be available for direct utilisation for SGD in the Karoo, without impacting on existing user groups including aquatic ecosystems. The low assurance of yield means moreover that abstraction from non-perennial rivers will be difficult. For the purposes of this scientific assessment, it is assumed therefore that surface water abstraction to support new development in the study area is not a viable option. Even if water for the industry itself is sourced outside of this area, the increase in domestic demands for potable water are likely to impose impacts on both groundwater and surface water resources and there is a high risk of water shortages in large parts of the study area.

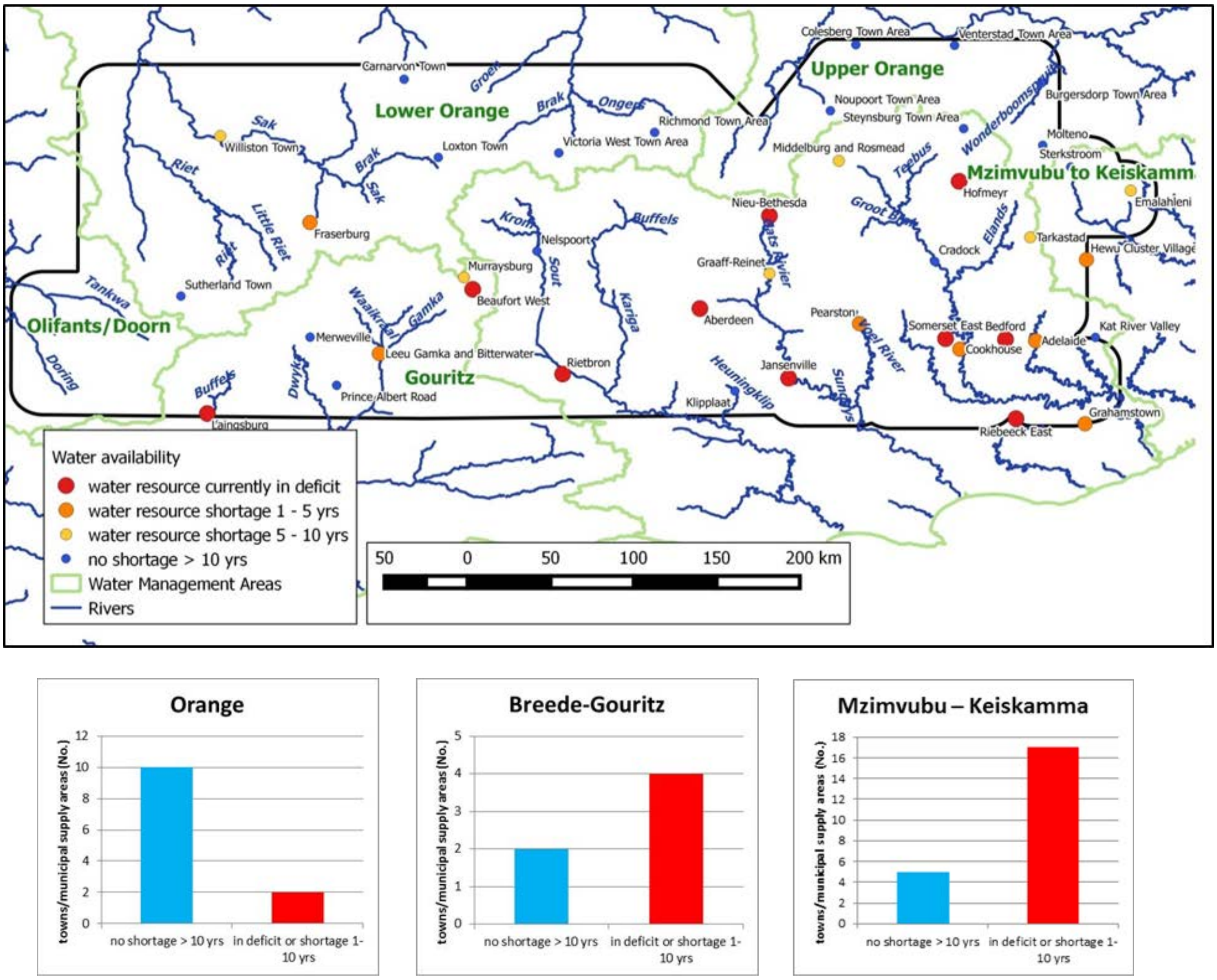

Figure 5.23: "All Towns" data from the DWS showing current water availability and predicted shortages for each town or settlement in the study area. Each point represents a municipal supply scheme which, depending on the municipality includes domestic, industrial and agricultural use. Bar graphs summarise water use per WMA.

Groundwater use in the study area is considered underestimated because a substantial portion of the resource is either not licensed in terms of the National Water Act 36 of 1998 (NWA) (RSA, 1998a) or is considered Schedule 1 use which does not require licensing. It is therefore recommended that a study which validates and verifies water use be initiated as a priority within the study area. Furthermore, it is imperative that the Ecological Reserve is quantified where such information gaps exist within the study area such that resource availability in terms of both surface and groundwater is more accurately estimated.

5.3.2 Inter-catchment water transfers

The Gariep Dam, located on the Orange or Gariep River just north of the boundary and ~50 km east of Colesberg (Figure 5.24), is the largest dam in the country and transfers water into the study area, via the Orange-Fish tunnel. This supplementary water passes into the Grassridge Dam on the Groot Brak River, a tributary of the Great Fish River. It is used both to augment scarce local resources as well as for water quality management purposes to reduce river salinity (SSI, 2012). It passes through the Fish to Tsitsikamma WMA as far south as the coastal areas and forms part of the Algoa Water

Supply System, which provides water to the Gamtoos Irrigation Board, 1.1 million people in the Nelson Mandela Bay Municipality (NMBM) for domestic use and for use by more than 373 industries, the Coega Industrial Development Zone and several smaller towns within the Kouga Municipality area (DWS website).

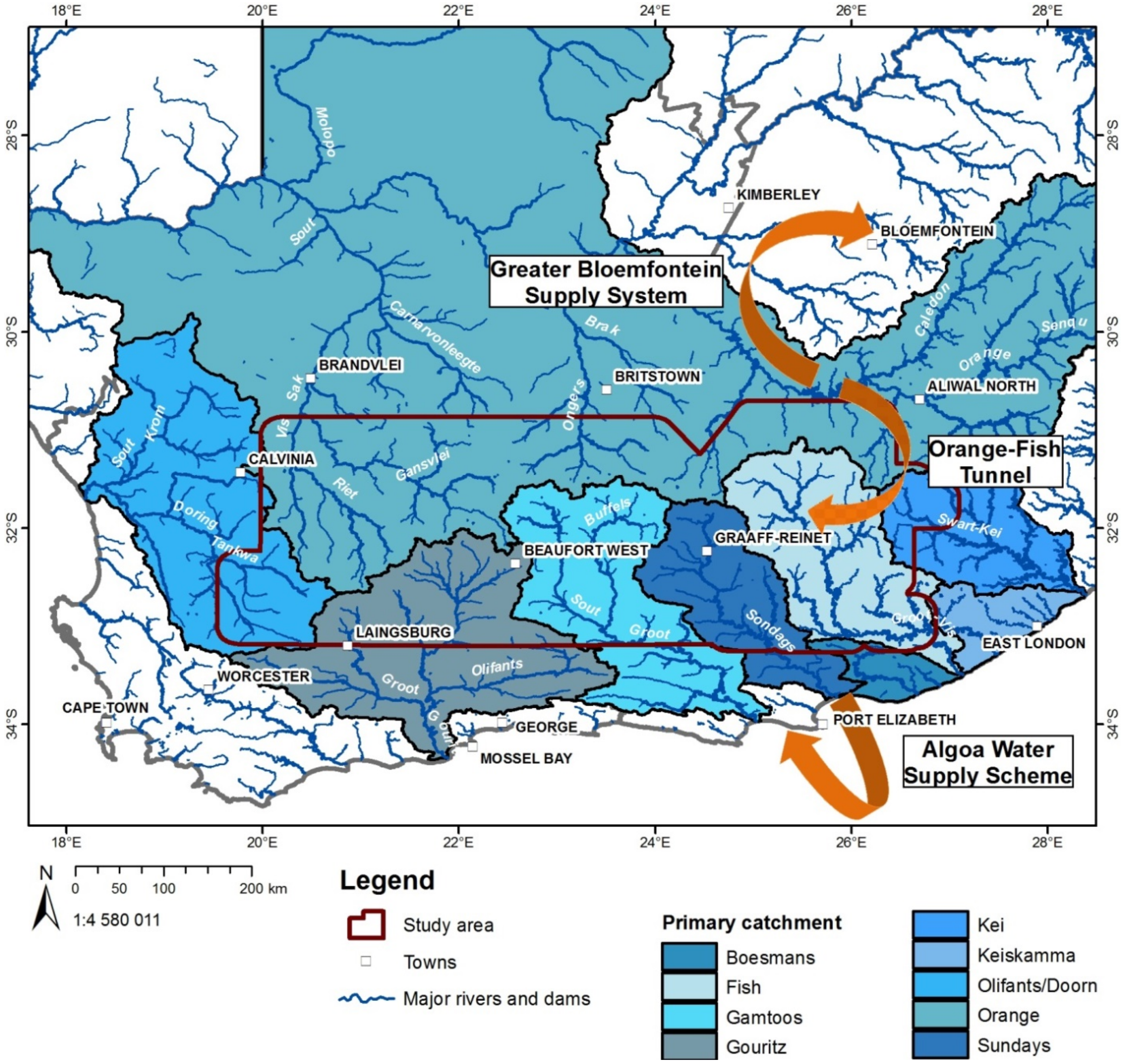

Figure 5.24: Inter-catchment transfers between the Orange and the Fish-Tsitsikamma Water Management Areas, traversing the study area.

The relevance of these water resource transfers through the study area is that they create potential flow pathways for contaminants generated in their catchment, including those potentially associated with shale gas exploration and/or production (Section 5.5.2).

5.3.3 Climate change and water resources

An assessment of the effects of projected climate change on streamflows in the study area was undertaken as part of this scientific assessment, and the results are indicated in Figure 5.26 and 5.27.

Figure 5.25, which presents projected streamflow changes in mm equivalents, shows marked decreases in streamflows in the east, moderate decreases to negligible changes in the central areas, and slight increases in the south-western corner. It should, however, be borne in mind that these projected changes come off a very low base of streamflows in this semi-arid area, and when the projected changes are expressed as percentage changes (Figure 5.26), the map shows decreases over 80% of the study area, varying from 15 to 60% of Mean Total Streamflow. These are significant projected decreases over much of the study area in an environment experiencing already stressed surface water resources.

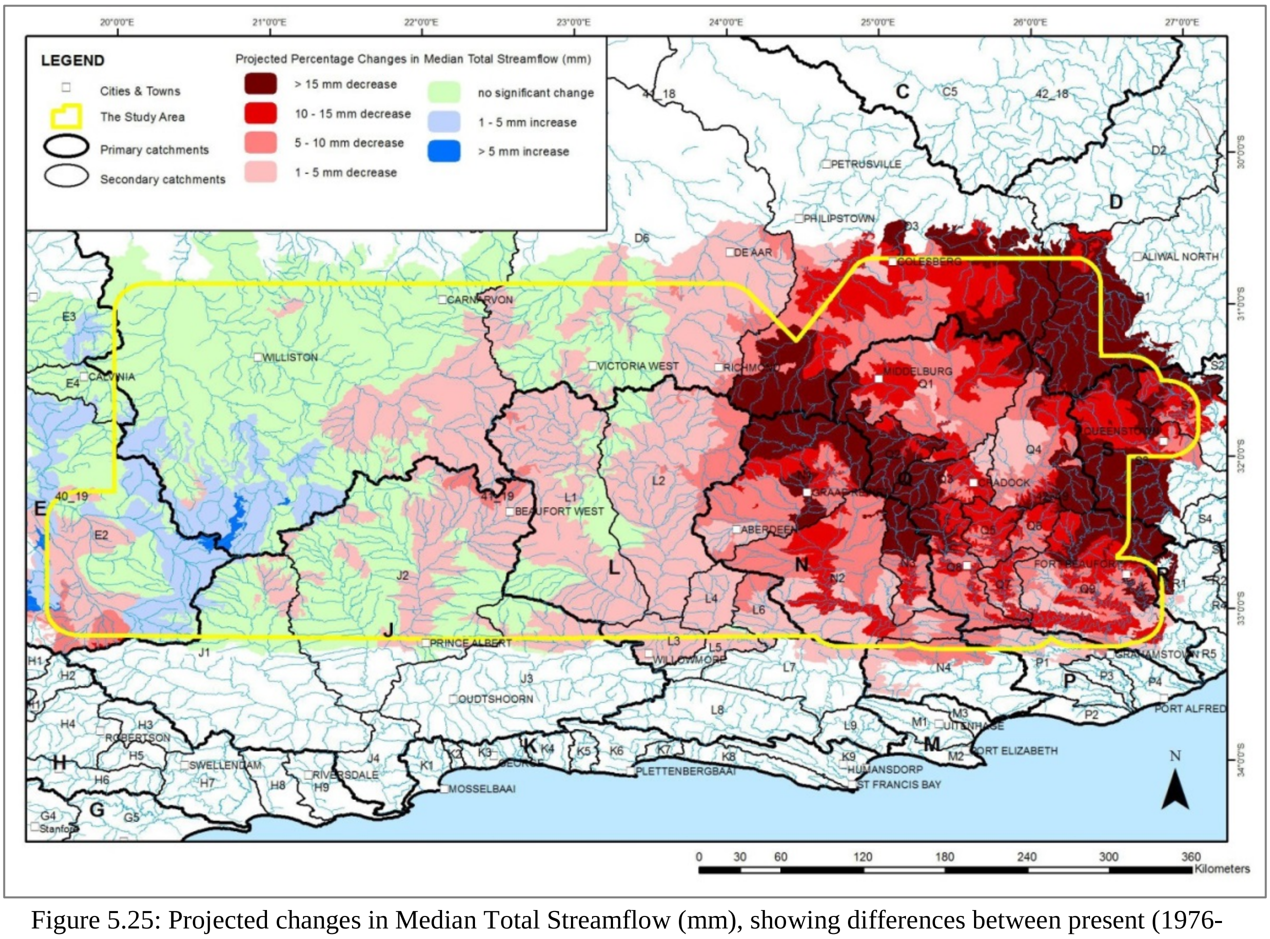

Figure 5.25: Projected changes in Median Total Streamflow (mm), showing differences between present (1976-2005) and intermediate future (2016-2045) climate scenarios, with data based on averages of changes from five GCMs (i.e. CCCma, CNRM, ICHEC, NCC, NOAA). Data derived for this study by R.E. Schulze.

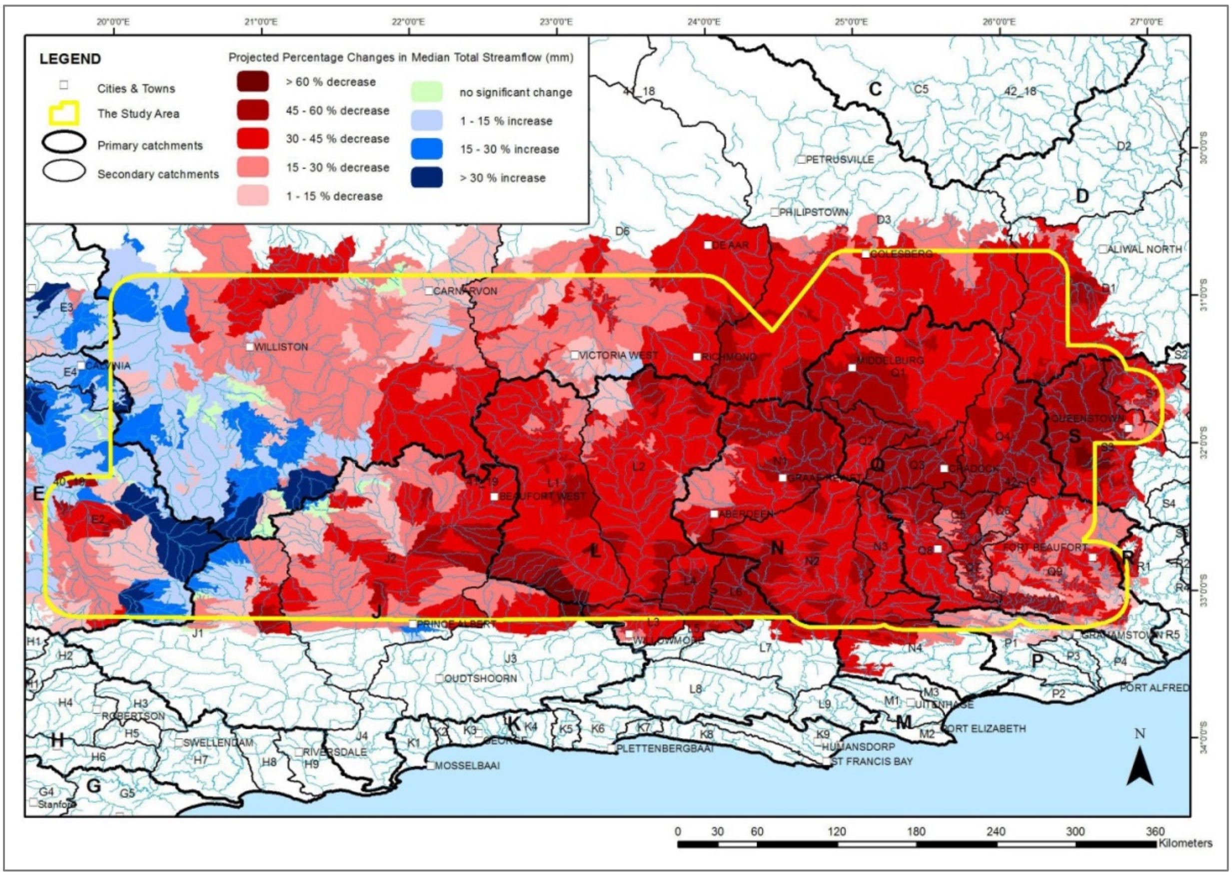

Figure 5.26: Projected percentage changes in Median Total Streamflow, showing differences between present (1976-2005) and intermediate future (2016-2045) climate scenarios, with data based on averages of changes from five GCMs (i.e. CCCma, CNRM, ICHEC, NCC, NOAA). Data derived for this study by R.E. Schulze.

5.3.4 Summary of water resource availability for SGD

It has been shown in Section 5.3.1 that while the projection of water demands for the next decade in regard to the Orange WMA predict shortages in only a few of its municipal areas/towns, those for the Breede-Gouritz and Mzimvubu-Tsitsikamma WMAs that span the study area present greater concerns. The water resources in these WMAs are either already in deficit, or water shortages are expected in the near future. This finding is exacerbated by the observation in Section 5.3.3 that streamflow in large parts of the study area is projected to decrease as a result of climate change.

It is apparent, therefore, that additional surface water resources are unlikely to be available for direct utilisation in a developing shale gas industry in the Karoo, without impacting on existing users including aquatic ecosystems.

The impression given in Figure 5.21 that many of the Quaternary catchments in the study area experience a low (<25%) level of groundwater stress must be tempered by consideration of the fact that the quantum of groundwater use outside of the formal town water supply systems served by motorised and metered production boreholes is not known. Produced by windpumps, the aggregate volume of groundwater supplied from these sources mainly for livestock watering purposes (Schedule

1 use) is indeterminable. The various factors that inform the veracity of any attempted quantification of this use are described in the Agriculture Chapter by Oettle et al. (2016), and apart from a reliable value for the total number of functional boreholes in the study area, it is hampered mainly by a paucity of borehole yield data. These circumstances indicate that a different approach is required to arrive at even a coarse estimate of this use.

Oettle et al. (2016) reports a population of ~7 million sheep as underpinning the Karoo's economy. If only a third of this population occurs in the study area, then applying the per capita demand of 5 L/d per large stock unit (Section 5.2.4) returns a daily water requirement of ~11 700 m^3 per day, or ~4.26 million m^3 per annum. To this must be added the municipal water requirements that in many instances are solely provided from groundwater sources, and account in the main for the cluster of groundwater stressed Quaternary catchments in the south-central part of the study area (Figure 5.21).

Using a strict livestock watering versus shale gas production well comparison, just 21 of the latter (at 0.2 million m^3 per annum each as per Table 5.4) will consume the coarse estimate (~4.26 million m^3 per annum) of Schedule 1 use for livestock watering in the whole study area. It is apparent, therefore, that a similar prognosis as for surface water availability applies also to the availability of groundwater resources within the context of SGD.

5.4 Relevant legislation, regulation and practice

The following discussion only addresses legislation of direct relevance to this Chapter. Other legislation which may also address water resources, e.g. in regard to the environment (Holness et al., 2016), waste (Oelofse et al., 2016) and agriculture (Oettle et al., 2016), are addressed in those respective Chapters where these are most relevant. In this Chapter, legislation and regulations relevant to water *per se* are discussed in the context of international law, the Constitution and other relevant laws in South Africa (in this order).

5.4.1 International law

International customary law and international conventions and treaties are important in the South African context. International customary law principles such as the polluter pays principle, the precautionary principle and the preventive principle have been enumerated in Section 2 of the National Environmental Management Act 107 of 1998 (NEMA, RSA, 1998b). In South Africa these principles apply to 'the actions of all organs of state that may significantly affect the environment', and not just the Department of Environmental Affairs (DEA), which administers this particular statute.

In terms of international convention, South Africa is party to the international convention on wetlands of international importance especially as waterfowl habitat, 'the Ramsar Convention', which provides for the designation of wetlands of international significance by state parties to the convention. South Africa has designated 20 wetlands under the treaty.

The South African Development Community (SADC) revised protocol on shared watercourses of 2000 and the United Nations Convention on the Law of the Non-navigational uses of international watercourses of 1997, are other relevant treaties for the Orange River that traverses the study area.

In terms of the SADC protocol, the Orange River is an international watercourse and Lesotho, South Africa, Namibia and Botswana are all watercourse states with respect to this river. According to this protocol, the State Parties recognise the principle of the unity and coherence of each shared watercourse and in accordance with this principle, undertake to harmonise the water uses in the shared watercourses and to ensure that all necessary interventions are consistent with the sustainable development of all Watercourse States and observe the objectives of regional integration and harmonisation of their socio-economic policies and plans.

The UN Convention of 1997 codified international water law and is a framework agreement, which allows for ad hoc watercourse agreements to be adopted for specific international watercourses. The substantive obligations of the UN convention are that watercourse states (a) may utilise an international watercourse in an equitable and reasonable manner, (b) should not cause significant harm to other states using the same watercourse, and (c) have to protect international watercourses and their ecosystems.

5.4.2 Constitution of the Republic of South Africa

The Constitution of the Republic of South Africa (Act 108 of 1996) (the Constitution) is the supreme law of South Africa and the Bill of Rights, contained within it, is the cornerstone of democracy in South Africa. The Constitution, with its environmental right, is a crucial enactment, as are a number of other acts that regulate the following inter-related areas of environmental concern.

5.4.3 Relevant South African laws

5.4.3.1 <u>The National Water Act</u>

The National Water Act 36 of 1998 (NWA) (RSA, 1998a) provides legislation to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner, for the benefit of all persons and in accordance with its constitutional mandate. The act defines a "water resource" to include a watercourse, surface water, estuary, or aquifer; and watercourses include rivers, springs, wetlands, dams or any collection of water that the Minister declares to be a watercourse. This Act is administered by the DWS. Sections 2 (g) and (h) specifies the "protection of the aquatic and associated ecosystems and their biological diversity" and "reducing and preventing pollution and degradation of water resources" respectively (RSA, 1998a).Water resources are primarily managed and protected in the NWA by the need to obtain a license for permissible 'water use', except in cases where a license is not required, for example where a 'General Authorisation' (GA) or 'schedule 1 use' has been issued. Water use is defined in Section 21 of the NWA and includes:

- (*a*) taking water from a water resource;
- (*b*) storing water;
- (*c*) impeding or diverting the flow of water in a watercourse;
- (*d*) engaging in a stream flow reduction activity contemplated in Section 36;
- (*e*) engaging in a controlled activity identified as such in Section 37(1) or declared under Section 38(1);
- (*f*) discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit;
- (*g*) disposing of waste in a manner which may detrimentally impact on a water resource;

(*h*) disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process;
(*i*) altering the bed, banks, course or characteristics of a watercourse;
(*j*) removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people; and
(*k*) using water for recreational purposes.

Once an applicant falls into any one or more of the items listed above the Minister may issue conditions for the granting of a license. Section 29 of the NWA sets out conditions that can be attached to GA's and licenses, relating to the protection of the water resource, to water management and to return flow, to discharge or disposal of waste, in the case of a controlled activity, in the case of taking or storage of water and in the case of a license.

The DWS is in the process of formulating its own regulations regarding oil and gas exploration and development (thus including SGD). It has invoked Section 38 of the NWA (RSA, 1998a) to declare "The exploration and or production of onshore naturally occurring hydrocarbons that requires stimulation, including but not limited to fracking and or underground gasification, to extract, and any activity incidental thereto that may impact detrimentally on the water resource." as a controlled activity. This was published in General Notice No. 999 (RSA, 2015b) as Section 37 (e) of the NWA (RSA, 1998a). Declaration of unconventional oil and gas extraction as a controlled activity means that water use licenses will be required for SGD.

It is important to note that Part 3 of Chapter 3 of the NWA provides for the determination of a Reserve and related matters (Sections 16 to 18), before the issuing of a license. This means that Reserve determinations on groundwater and surface water resources in the SGD areas would be required. Sections 19 and 20 of the NWA require shale gas operators to prevent pollution incidents and emergency incidents and outlines how operators should act in the case of an emergency incident.

Lastly, Chapter 14 of the NWA (Sections 137 to 145) titled Monitoring, Assessment and Information is particularly relevant to fracking. Monitoring, recording, assessing and disseminating information on water resources is critically important for achieving the objects of the Act. The Minister of DWS must establish national monitoring systems and national information systems, each covering a different aspect of water resources, such as a national register of water use authorisations, or an information system on the quantity and quality of all water resources. The Minister must also establish mechanisms and procedures to coordinate the monitoring of water resources after consultation with the relevant organs of state including water management institutions and existing and potential users of water. Key regulations important for fracking under the NWA, includes GN 704. The regulations on use of water for mining and related activities aimed at the protection of water resources (GN 704/1999 in Government Gazette of 4 June 1999) is aimed at protecting water resources. The following regulations of GN 704 are relevant:

- *Regulation 4*, with restrictions on locality, specifies that no person in control of a mine or activity may locate or place any residue deposit, dam, reservoir. together with any associated structure or any other facility within the 1:100 year floodline or within a horizontal distance of 100 m from any watercourse or estuary, borehole or well, excluding boreholes or wells drilled specifically to monitor the pollution of groundwater, or on water-logged ground, or on ground likely to become water-logged, undermined, unstable or cracked. It then goes on to specify more details on locality.

- *Regulation 5* restricts the use of materials and specifies that no person in control of a mine or activity may use any residue or substance which causes or is likely to cause pollution of a water resource for the construction of any dam or other impoundment or any embankment, road or railway, or for any other purpose which is likely to cause pollution of a water resource.
- *Regulation 6* specifies capacity requirements for clean and dirty water systems; and
- *Regulation 7* sets out specific requirements for the protection of water resources.

Other relevant regulations are GN 1199 (18 December 2009), which specifies conditions for impeding or diverting flow or altering the bed, banks, course or characteristics of a watercourse to persons using water under Sections 21 (c) and (i) of the NWA. In these regulations, no water use is allowed within a 500 m radius from the boundary of a wetland. Also, altering the bed, banks, course or characteristics of a watercourse is not allowed within the 1:100 floodline or within the riparian habitat, whichever is the greatest.

5.4.3.2 The Water Services Act

The Water Services Act 108 of 1997 (WSA) (RSA, 1997b) governs the provision of water services in the country. This act is also administered by the DWS. Section 2 (j) seeks to promote "…… effective water resource management and conservation."

According to the WSA, Water Services Providers (i.e. the municipalities that are supplying their communities with water) must ensure that water of a specific quality is provided (SANS, 2015a: 2015b), must ensure assurance of supply and must also ensure sanitation in their jurisdictions. If SGD occurs in a specific area, there will be an additional strain on the infrastructure and resources for water services delivery and sanitation when there is an influx of people. Additionally, the issue of waste water treatment at waste water treatment works (WWTW's) should be considered, as these works do not currently have the capacity to treat received waste water. Treatment of fracking waste water would also not be possible at these plants due to the fact that the type of waste water emanating from fracking operations is different from waste water streams currently treated at the WWTW's. This aspect is dealt with in more detail by Oelofse et al. (2016). These are important strategic issues to take into consideration.

5.4.3.3 The Mineral Petroleum Resources Development Act

The exploration and development of mineral and petroleum resources is legislated for in the Mineral and Petroleum Resources Development Act 28 of 2002 (MPRDA) (RSA, 2002). All environmental management aspects, however, are dealt with in terms of the "One Environmental System" which became effective on 14 December 2014. The relevant principal features of the One Environmental System with respect to exploration and mining are:

- that all environment related aspects are to be regulated through one environmental system under NEMA and all environmental provisions are to be repealed from the MPRDA; and
- the Minister of Mineral Resources will issue environmental authorisations under NEMA.

It must be noted however, that the companies involved in SGD in the Karoo have all submitted their applications for exploration rights in terms of the MPRDA in 2011. At the time, Section 39 of the MPRDA required that an Environmental Management Plan (EMP) must be submitted as part of an application for a gas exploration right. These EMP's were submitted in 2011 as part of the applications for exploration rights. The applications are still pending, and even though Section 39 of the MPRDA was repealed, all pending applications must be finalised as if Section 39 was not repealed. Subsequently, in 2015, the Department of Mineral Resources (DMR) requested the applicant companies to carry out a review of their EMP reports to determine whether they comply with the requirements set out in Section 39(3) of the MPRDA. In terms of the One Environmental System, the environmental aspects associated with any new applications related to exploration and production of shale gas resources will be dealt with in terms of the provisions of NEMA, with DMR being the competent authority.

Section 2 (h) seeks to ensure "…... that the nation's mineral and petroleum resources are developed in an orderly and ecologically sustainable manner while promoting justifiable social and economic development" in accordance with Section 24 of the Constitution. Environmental management is addressed in Section 39, and sets out in Section 39(3) the requirements attendant on an Environmental Management Programme (EMPr) or an environmental management plan (EMP). It is important to note that the mining industry is a long established industry in South Africa; while the petroleum resources industry, particularly land based extraction is still in its infancy. As a result, while the MPRDA tackles both, much associated regulation, particularly that which covers environmental matters and water, tends to focus on mining activities and are silent on petroleum production activities.

Environmental Authorisations (EA's) are one of the key features of both the mining and petroleum regulatory regimes. Section 37 of the MPRDA states that all prospecting and mining operations must adhere to the environmental management principles of the NEMA while Section 38 states that any operator has a responsibility to manage environmental impacts and must as far as possible rehabilitate the environment affected by the operations. Section 39 calls for operators to conduct an EIA and submit an EMP where baseline information of the affected environment to determine protection and remedial measures must be established. Section 41 calls for operators to make financial provision for the remediation of environmental damage. An operator remains responsible for any environmental liability, pollution or ecological degradation and its management until the Minister of Mineral Resources has issued a closure certificate and no closure certificate may be issued until the Minister of Water and Sanitation has confirmed in writing that the provisions relating to health and safety and the management of potential pollution to water resources have been addressed (Section 43).

In 2015 specific regulations to govern petroleum exploration and production has been promulgated under the MPRDA – i.e. Regulations for Petroleum Exploration and Production, 2015 (GN R466). These petroleum exploration and production regulations prescribe standards and practices to ensure the safe exploration and production of oil (petroleum and other liquid hydrocarbons) and gas (coal bed methane (CBM) and shale gas). GN R466 is listed in Digital Addendum 5B for ease of reference. GN R466 specifies that an EIA be performed in potential areas of petroleum exploration and extraction, with specifics relating to water resource monitoring (sub-regulation 88), the management of drilling fluids (sub-regulation 109), fracking fluid disclosure (sub-regulation 113), fracture and fracturing fluid containment (sub-regulation 114), the management of fracturing fluids and flowback and produced fluids (sub-regulations 115 and 116) as well as regulations on the transportation and storage of fluids (sub-regulations 117 and 118).Sub-regulations 121 to 123 focuses on the management of water specifically while sub-regulations 124 to 126 focuses on waste management and spillage management. Sub-regulations 122(2) and 122(3) specify setback distances from water resources, which are discussed in more detail in Section 6. Sub-regulations 130 to 132 focus on well suspension and decommissioning, which are in the respectful view of the authors, inadequate. Disappointingly, no penalties are specified for non-compliance with these regulations, meaning that operators will not face any consequences for not complying with any of the provisions set out in these regulations.

5.4.3.4 The National Environmental Management Act

The requirements for Environmental Impact Assessment (EIA) under the National Environmental Act 107 of 1998 (NEMA) (RSA, 1998b) are also applicable in a water context. The principles in Section 2 of the NEMA apply to both the MPRDA and the NWA. An important principle is the precautionary ("risk-averse and cautious") approach, specifying that a risk-averse cautious approach is applied to development, which takes into account the limits of current knowledge about the consequences of decisions and actions. Another important principle is that the costs for remedying pollution, environmental degradation and consequent adverse health effects must be paid for by those responsible for harming the environment. Chapter 3 of the NEMA requires co-operative governance, which would be important if fracking is to be managed effectively between different spheres of government.

5.4.4 Regulatory water quality guidelines and standards

Water quality management in South Africa is based on two separate concepts: water quality guidelines, and water quality standards. The South African Water Quality Guidelines “serve as the primary source of information for determining the water quality requirements of different water uses and for the protection and maintenance of the health of aquatic ecosystems” (DWAF, 1996). Recognising that suitable quality may differ for different water users, separate guidelines are provided for domestic, recreational, industrial and agricultural (irrigation and livestock watering) use, as well as for maintenance of aquatic ecosystems. As the name implies, these are guidelines for best practice and are not legally binding.

In contrast, standards for drinking water and purification of waste waters and effluents are legislated and should therefore be binding. The SANS specifies the minimal quality of drinking water, defined in terms of microbiological, physical, chemical, and taste-and odour parameters at the point of delivery to the consumer. The assumption is that water of this quality will present an acceptable health risk for lifetime consumption. The Water Services Act 108 of 1997, updated as SANS (2015a: 2015b), requires that water provided by water services authorities such as municipalities meets the specified standards. It should be noted that these standards apply only to water to be delivered to the consumer, and not to water in rivers or aquifers, where only the relevant guidelines apply.

Standards were set in the 1956 Water Act for some 23 constituents in effluents and waste waters entering a stream. While the updated version (DWA, 2013) modifies the legal limits of some constituents, no additional constituents are considered. The values set for most or all of the constituents listed in the current list are derived from the South African Guidelines for Aquatic Ecosystems (DWAF, 1996).

5.5 Key potential impacts and their mitigation

Any discussion of key potential impacts on water resources and their mitigation must be prefaced by a discussion of the hydrologic, geologic, hydrogeologic and relevant technological aspects that frame the development of a shale gas industry. To this end, the following material provides a synthesis of the geologic environment to aid conceptualisation of the key potential impacts of specific relevance to the Karoo Basin. It is followed by a similar synthesis of the other aspects attendant on the development of shale gas resources. This necessarily draws to some extent on international experience.

The following assumptions regarding each scenario form an important backdrop to the description of potential impacts associated with each scenario, and feed into the later risk assessment associated with each impact:

- Scenario 0 (Reference Case): It is assumed that in this “no shale gas development” scenario, water resources in the Karoo region remain largely unchanged in terms of resource allocation, especially given that surface waters in the region are considered over-allocated in any case, but that water in the region will be affected by climate change. Climate change models suggest that climate change will result in increased frequency of extreme events such as droughts and floods. In this context it is assumed with low confidence levels (because detailed climate change scenarios have not been run for the study area), that water resources are highly sensitive to climate change, primarily because any change in rainfall, be it positive or negative, is amplified in the streamflow response and flow variability, and is further amplified in the groundwater recharge response. In the case of surface water, as rain intensities increase, this may in some areas translate into higher levels of erosion and sediment transport, and higher siltation rates within impoundments. It is also likely that the value of groundwater resources in an increasingly arid Karoo environment will become greater compared to surface water. Climate change impacts would apply to all scenarios.
- Scenario 1 (Exploration Only): In this scenario, limited seismic exploration only occurs, with vertical stratigraphic and appraisal wells being drilled.
- Scenario 2 (Small Gas): Seismic exploration, vertical stratigraphic wells and limited fracking in horizontal sections, with a 110 ha footprint for each of 55 wellpads describes this scenario.
- Scenario 3 (Big Gas): Seismic exploration, vertical stratigraphic wells and fracking in horizontal sections, with a 820 ha area wellpad coverage; 410 wellpads constructed.

In all of the above, it is assumed that activities would be governed by a responsibly authorised EMPr but that, as stated in Burns et al. (2016), 30 years after the start of exploration, abandoned wellpads would be audited and if found to have achieved required rehabilitation targets in accordance with relevant legislation and regulations, monitoring to verify this compliance will continue for at least another 10 years. Importantly, it is assumed that further auditing of these wellpads then ceases.

5.5.1 Groundwater issues

The primary issues of concern with respect to SGD are the contamination of shallow groundwater resources and the supply of water for drilling and fracking activities. Associated with the former is possible hydraulic connectivity between deep and shallow formations and the disposal of flowback and produced water. Vengosh et al. (2013) identified the management of waste waters as one of the main issues confronting the shale gas industry, with post-fracking incidents related to surface spills or faulty casing and poor well maintenance accounting for all proven contamination to date.

The growth of the USA shale gas industry proceeded in the absence of baseline water resources monitoring studies to establish a reference of 'pre-industry' water quality. This compromises any subsequent attempt to link observed instances of impaired water resources quality (especially sub-surface) with the industry itself. This makes it very difficult to prove that certain elevated constituents in water are as a result of SGD/production (Stephens, 2015). The situation is exacerbated in instances where SGD proceeds in an area where the existence and position of 'historical' deep wells was not required to be documented; Davies (2011) reports >180 000 such wells in Pennsylvania. It is reasonable to presume that a proportion of these were improperly abandoned, providing connecting pathways to shallower aquifers. This is not the case in the study area, where existing boreholes established for water supply purposes, including those that have been abandoned, seldom exceed a depth of 150 m.

Vengosh et al. (2014) investigated stray gas contamination of shallow aquifers, contamination of groundwater and surface water from spills, leaks and waste water, the accumulation of toxic or radioactive contaminants in soils and stream sediments near disposal or spill sites and the over-exploitation of water resources to supply drilling and fracking operations. Evidence was found of stray gas migration, contamination of water from surface spills and leaks and accumulation of contaminants in soils/sediments but conclude that contamination of water resources by fracking itself "remains controversial".

Migration of contaminants from the 'fracked zone' along natural or induced pathways seems to be the least likely cause of water contamination according to a number of researchers (Osborn et al., 2011; RS&RAE, 2012; Brantley et al., 2014). Atangana and Van Tonder (2014) suggest rather drastically and on purely theoretical grounds, however, that "…... in the case of the Karoo, fracking will only be successful if and only if the upward methane and fracking fluid migration can be controlled, for example, by plugging the entire fracked reservoir with cement." This opinion is shared by Van Tonder et al. (n.d.). It is also worth noting that Warner et al. (2012) report the natural migration of brines (TDS of 10 000 to 343 000 mg/L) from the Marcellus Shale Formation through >1 200 m of sedimentary strata into shallow aquifers in north-eastern Pennsylvania. Nevertheless, the main possible causes of contamination are considered to be the following:

- surface spills and leaks (Metzger, 2011), which should be of short-term duration and relatively easy to identify and quickly remedied;
- compromised production well integrity associated with leaky casings and annular seals (Ingraffea 2013), which are more difficult to identify and result in longer-term contamination; and
- spent production wells that develop structural defects following decommissioning (Ingraffea, 2013), and represent an insidious long-term threat.

The pathways represented by the afore-mentioned 'threats' are illustrated in Figure 5.27. It is the cumulative impact of many wells in various phases of development in comparatively small areas (greater density) that represents the greater concern and risk profile (Kibble et al., 2013).

The data presented in Burns et al. (2016) have been evaluated to derive a typical value of water use required for the drilling and construction of various types of wells associated with SGD. The results are presented in Table 5.3. If it is assumed that a fracked well is completed in 30 days, then the total water use of 16 330 m^3 (without re-use) is in reasonable agreement with the average per well of ~17 600 m^3 reported by King (2012), and comfortably in the ranges 13 000 to 19 000 m^3 reported by Osborn et al. (2011) for the Marcellus Shale, the 9 800 to 24 600 m^3 reported in Table 5.1, and the 10 000 to 30 000 m^3 reported in Burns et al. (2016).

The values presented in Table 5.3 are readily aggregated to a variety of situations, e.g. per annum, per campaign, per scenario (Small or Big Gas) using the number of wells as multiplier. It is on this basis that the water use per drill rig and the total water use for a Small Gas scenario and a Big Gas scenario campaign as presented in Table 5.4 is derived.

Table 5.3: Summary of water use by shale gas well type.

Type of well	**Depth/length (m)**	**Water use**					
		Without re-use			**With re-use**		
		L/s	**m^3/d**	**m^3/m(1)**	**L/s**	**m^3/d**	**m^3/m(1)**
Stratigraphic well(2)	3 000	0.3	26	778	0.2	17	518
Vertical well(3)	3 000	0.3	26	778	0.2	17	518
Fracked vertical + horizontal well(4)	3 000 + 1 500	6.3	544	16 330	4.3	372	11 146

(1) m^3 per month
(2) Type “X” well illustrated in Figure 1.24 (Burns et al., 2016)
(3) Type “Y” well illustrated in Figure 1.24 (Burns et al., 2016)
(4) Type “Y” + “Z” well illustrated in Figure 1.24 (Burns et al., 2016)

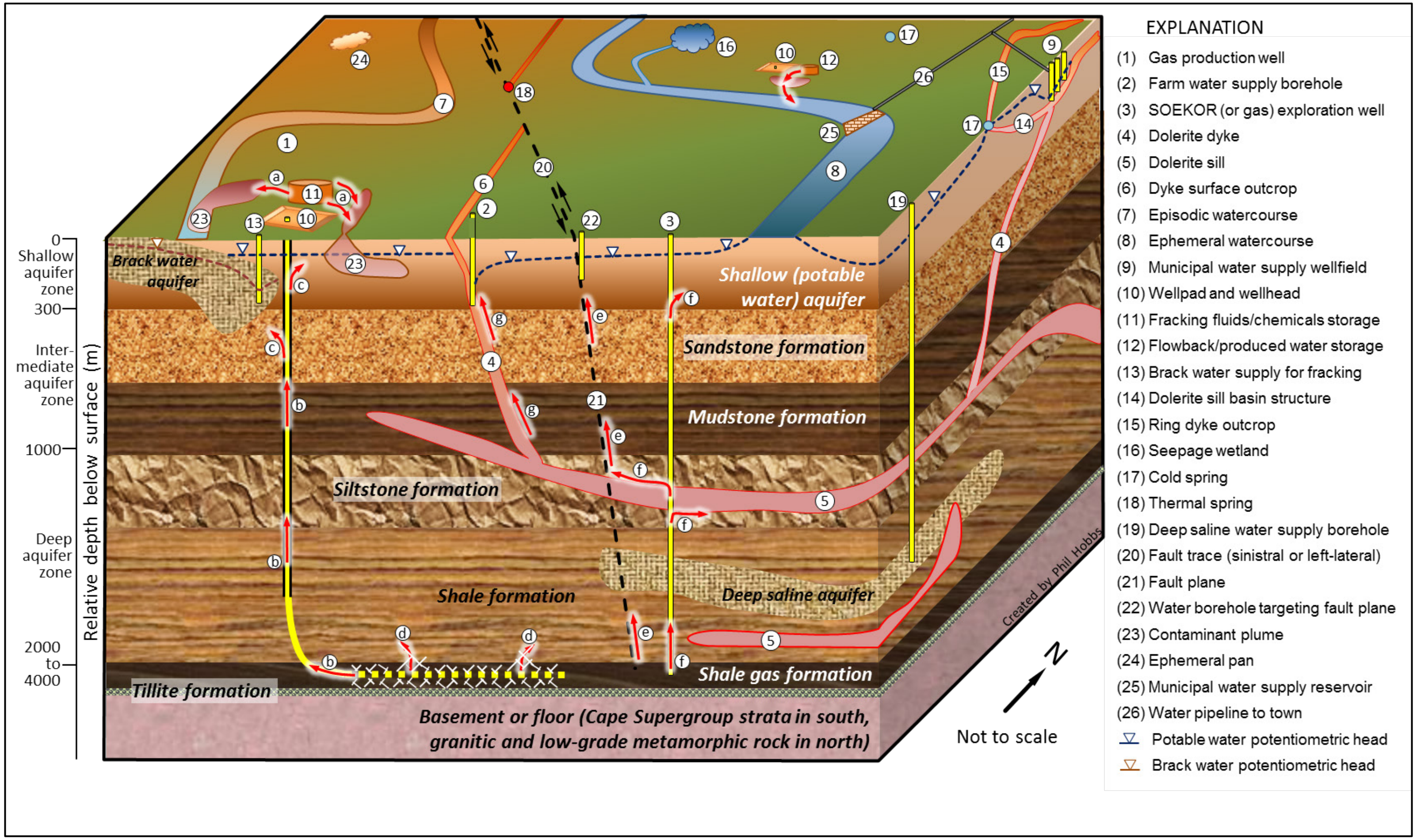

Figure 5.27: Schematic block diagram illustrating various features associated with the surface water and groundwater environments as these relate to SGD activities. The possible contaminant pathways (red arrows) and plumes (feature 23) are conceptual and exaggerated for explanatory purposes. The lithostratigraphic succession is similarly for illustrative purposes, whereas in reality the various formations comprise a mixture of sedimentary rock types, and are also not uniformly thick or necessarily horizontal. Features 3 and 19 might be artesian. The possible contaminant pathways are identified as (a) surface spills at the wellpad, (b) flowback and produced water via a production well, (c) leakage via faulty annular seals in production wells, (d) migration via hydraulic fractures, (e) preferential migration along fault planes, (f) escape/leakage via old (possibly uncased) oil and gas exploration wells, and (g) preferential migration along dyke/sill contact zones.

Table 5.4: Summary of water use per drill rig by type of shale gas campaign.

Water use application (campaign)	Period (years)	Per drill rig		Total	
		Without re-use m^3	With re-use m^3	Without re-use m^3	With re-use m^3
Exploration only	2	103 770	70 140	518 850	350 700
				5 drill rigs	
Small Gas	17	3 283 500	2 237 400	9 850 500	6 712 400
				3 drill rigs	
Big Gas	21	4 104 375	2 796 750	82 087 500	55 935 000
				20 drill rigs	

5.5.1.1 Exploration activities

The key impact of shale gas exploration activities is on water use. The water requirements, typically for activities such as geophysical exploration and stratigraphic drilling, are comparatively low. Water is required for purposes such as personnel/crew 'domestic' use (e.g. drinking/cooking water and ablutions), for access road construction and in the drilling of stratigraphic wells.

Impact: The water requirements for exploration activities can, in most instances, be readily met from groundwater resources in the vicinity of the exploration activities. For example, the water use for a geophysical campaign is mainly for personnel/crew 'domestic use'. Assuming a staff complement of 100 people, then their requirement of 150 L/d/capita amounts to 15 m^3/d. This can be met from a borehole delivering ~0.4 L/s in a 12-hour day. Similarly, the water requirement for stratigraphic drilling (without re-use), including that of 100 crew, amounts to ~26 m^3/d (Table 5.3). This again can be met from a borehole delivering 0.6 L/s per 12-hour day. The water requirement for road construction is estimated at ~30 m^3/d including 30 crew and sundry other use such as washing of vehicles. A single borehole delivering ~1 L/s per 12-hour day might therefore reasonably meet all of these requirements.

Mitigation: The impact of utilising groundwater at this scale for exploration activities is readily assessed by carrying out a hydrocensus (borehole survey) within a radius around the water supply borehole that is sufficient to encompass the likely area of influence (whether radial in the case of a homogeneous and isotropic aquifer, or linear in the case of a structural, e.g. dyke or fault, feature). The hydrocensus must include a quantitative assessment of water use from groundwater sources in the likely area of influence. Mitigation is indicated in instances where a reduction in water availability from a source is attributable to groundwater use for SGD activities, in which case the deficit must be compensated for based on the results of a groundwater use monitoring programme.

5.5.1.2 Appraisal activities

Shale gas appraisal activities have a higher water demand as these activities include the fracking of appraisal wells (Burns et al., 2016, Subsection 1.4.3.2.2.1). The fracking itself poses a greater risk to the environment than stratigraphic drilling, and is therefore identified as having a key potential impact. The associated risks are identified in Subsection 5.5.1 and illustrated in Figure 5.27. These comprise mainly the storage and handling of chemicals (used in the fracking process) on the wellpad, and the escape of flowback and produced water from the fracked section of bore via a number of pathways.

Impact: The water requirement for a fracked well is estimated at 544 m^3/d (without re-use). This amounts to a borehole yield of ~13 L/s per 12-hour day. Water supply boreholes of this class in the Karoo environment are scarce, and would likely produce groundwater with a quality suitable for most other uses, SGD, rendering their application for SGD highly contentious.

The storage and handling of chemicals on the wellpad poses a risk of their accidental spillage and escape into the environment if not contained.

The fracking of appraisal wells will not occur on the same scale as that of potential production wells with multiple horizontal sections, and the risk from this activity is therefore not considered as great as in the latter instance. Nevertheless, the risk is not inconsequential, and must be mitigated.

Mitigation: The water requirement is readily mitigated by sourcing water outside of the study area, necessarily requiring its importation into the study area. A possible alternative is the use of municipal waste water procured from local municipalities or, less likely, the utilisation of saline groundwater resources in the study area.

The comparatively short duration and smaller scale of the chemicals storage and handling activity provides a measure of risk reduction in addition to the wellpad protection measures advocated in Table 5.9. The latter include on-surface practices such as lining the wellpad with impermeable material and storing chemicals in bunded tanks that are regularly inspected for leakage.

The impact of fracking is mitigated by the implementation of the raft of measures described in Table 5.9. The most important of these are adherence to sound well construction practices to ensure the integrity of annular seals, and the setback of wells and their horizontal sections from geological structures (mainly faults and dykes), springs and municipal wellfields.

5.5.1.3 <u>Development and production activities</u>

SGD and production comprises similar activities as are associated with appraisal (Subsection 5.5.1.2), but at a significantly larger scale and intensity. The impacts as identified for appraisal activities are therefore equally relevant to development and production, but are an order of magnitude or even greater in terms of potential risk and impact. For example, a production gas well may comprise multiple fracked horizontal sections (laterals) radiating from one vertical bore (although it should be noted that there are multiple configurations for drilling horizontal wells from a wellpad). Further, the duration and geographic footprint of development and production is much longer and wider, respectively, than that of appraisal activities. Amongst other factors, this requires the establishment of a denser access road network. The volume of chemicals stored and handled on the wellpad are similarly much greater.

Impact: The substantial water requirement for either a Small or Big Gas scenario can realistically only be met by sourcing and importing water from outside of the study area.

The greater and more prolonged level of activity spent on a production well increases the risk of unintended accidental spillage on the wellpad.

The scale of fracking associated with the establishment of a gas production well indicates the return of substantially greater volumes of flowback and produced water to surface via the wellbore, compared to an appraisal well. The risk of leakage of contaminated water into the sub-surface via a compromised annular seal (resulting in a loss of well integrity) is therefore significant, and escalates with the scale and duration of SGD.

Mitigation: Water re-use and an advance to techniques that are not water-dependent provide a measure of mitigation for the reliance on an adequate water supply.

The facilities for chemicals storage (e.g. tanks on surface with retaining bunds) required by appropriate regulations (Oelofse et al., 2016) and handling provides a measure of risk reduction. Together with other wellpad protection measures such as lining of the wellpad with impermeable material provides for mitigation of this risk and impact.

As in the case of appraisal wells; the impact of fracking is mitigated by the implementation of numerous measures described in Table 5.9. The most important of these are adherence to sound well construction practices to ensure the integrity of annular seals, and the setback of wells and their horizontal sections from geological structures (mainly faults and dykes), springs, wetlands and municipal wellfields. Further mitigation is provided by the hydrocensus (borehole survey) and baseline data collection activity as well as the intensive geophysical investigations, both of which precede production well drilling and development.

5.5.1.4 <u>Post-development and -production activities</u>

These activities address the legacy of SGD once production ceases. The key potential impact at this stage will be the long-term risk of contamination to groundwater resources from defunct production wells.

Impact: The risk of failure of production well annular seals resulting in the leakage of contaminated produced water in the sub-surface increases with the age of a well. It also increases with the number of such wells in the environment.

Mitigation: The impact associated with the failure of defunct production wells requires the implementation of an effective adaptive management plan based on the results of a groundwater monitoring programme that will be maintained in this stage. Such monitoring will target not only the ageing production wells, but also dedicated monitoring wells constructed for the purpose of detection of contamination. The baseline groundwater chemistry data collected prior to SGD will serve as reference for such detection.

Funding for long-term monitoring and maintenance interventions must be assured at the outset of SGD involving fracking. Possible mechanisms whereby this might be achieved would be via a long-term, dedicated Trust Fund, or alternatively through bond/insurance schemes covering long-term liabilities in case of catastrophic failure.

5.5.2 Indirect groundwater impacts

Indirect impacts are mainly associated with unintended accidental spillage of chemicals and waste water in transit to/from the wellpad along the transport routes that will include public roads. The impact of such incidents will depend on factors such as the magnitude of the spill, the nature of the spilled material, and the location in the landscape. For example, a spillage in proximity to a dolerite dyke or fault (where these intersect the transport route) is of greater hydrogeological significance and risk than were it to occur away from such features.

Impact: The occurrence of accidental spillage is not readily quantified beyond the observation that such incidents will occur.

Mitigation: Mitigation of the impact from unintended accidental spillages must be provided by suitably trained 'hazmat' teams that can be alerted to such incidents and that are equipped to contain the spillage within the environmental setting it occurs.

5.5.3 Surface water issues

5.5.3.1 <u>Overview of issues</u>

This section provides a broad overview of some of the issues associated with SGD that are most likely to be of concern from a surface water perspective. These are assessed in a more structured manner in the sections that follow, as well as in the Risk Assessment of Section 5.6.

Given the close interactions between surface and groundwater already described in Subsections 5.2.3 and 5.2.4, it is clear that some impacts to groundwater will affect surface water resources and *vice versa*. Clear pathways between these systems are illustrated conceptually in Figure 5.27, *inter alia,* in the form of springs, unconfined alluvial aquifers, water supply boreholes and faults.

The main pathways for groundwater-to-surface water contamination include:

- **Vertical pathways directly associated with stimulation wells**, as a result of flowback or produced water that discharges into surface systems. Such impacts are considered unlikely, on a site by site basis, as they would be associated with accidental spills or overflows that bypassed collection devices already included in site design. They would however be more likely as the density and scale of operations increased, and their occurrence would potentially be more likely in extreme conditions such as storm events. EPA (2015) notes that the most significant spill causes in the USA include equipment failure, human error, failure of container integrity, and other causes (e.g., weather and vandalism). The most common cause was equipment failure, specifically blowout preventer failure, corrosion, and failed valves. More than 30% of the 151 fracturing fluid or chemical spills cited were from fluid storage units (e.g. tanks, totes, and trailers). Enforced adherence by operators to legislation that requires the storage of waste in sealed systems would considerably reduce the likelihood of such impacts taking place.

  The main concern with flowback that enters surface water resources (e.g. passes into watercourses) would be from a **water quality** perspective. While Subsection 5.2.2.2 notes that water from deep aquifers is unlikely to have the high TDS concentrations reported from brines in the Marcellus Shale formations for example (TDS of 10 000 to 343 000 mg/L reported by Warner et al. (2012), limited data from deep (> 1000 m) boreholes in the Karoo described in Subsection 5.2.2.2 indicate that this water (classified as "moderately saline" and with a TDS range of 3 000 to 10 000 mg/L) would still have a significantly higher salinity than the range for Karoo surface waters (the DWS water chemistry database cited in Subsection 5.2.3.2 lists a median conductivity of 504 mS/m, which is a TDS of approximately 2850 mg /L for one of the more saline systems in the study area). Inflows of moderately saline produced water into such systems would (depending on the volume discharged compared to natural flows) result in a substantial increase in salinity, well beyond the natural tolerance ranges for aquatic and riparian species, as well as fitness for use in agriculture and as drinking water. Vengosh et al. (2014) commented too that spills of saline flowback and/or produced water could have permanent effects on soil quality, potentially areas in which vegetation could not establish. Such effects could increase soil erosion, particularly in areas prone to high runoff.

Naturally occurring chemicals in produced water included in flowback might include chemicals from deep formations, such as brines, metals, metalloids and volatile organic compounds, again with negative implications for surface water resources in the event that they passed into these systems – high uncertainty exists however as to the kinds of chemicals expected in produced water. Data presented in Subsection 5.2.2.2 note the presence of naturally occurring uranium, radon, arsenic and methane in groundwater samples from some areas of the Karoo and these might well therefore be present in produced water.

Since large volumes of the fluids are utilised, and increase in direct relation to the number of wells, substantial downstream loading of aquatic resources by these chemicals would be possible in an accidental release scenario. Where such releases were the result of floods, dilution by floodwaters might reduce short term toxicity but in the case of conservative (i.e. chemically stable over time) chemicals, they could accumulate in downstream areas such as dams, where evapo-concentration would occur.

Although contamination during flood events would be somewhat diluted, downstream loading would potentially still be high and flood flows would increase the rate of transport through the system as well as potentially exposing shallow water aquifers along flow pathways to infiltration with contaminated water. Brantley et al. (2014), discussing the impacts of fracking on water resources in Pennsylvania, noted that surface leakage into bedrock fractures poses a high risk for contaminant transport into groundwater, and is a more likely transport mechanism than upflows from deep aquifers through geological media.

- **Vertical pathways linking zones of contaminated groundwater with surface resources** – these might include springs (warm and cold) as well as artesian wells and surface supply boreholes, although researchers including RS&RAE (2012) and Brantley et al. (2014) suggest that these pathways seem to be the least likely cause of water contamination, Brantley et al. (2014) did show tracer migration over a distance of 1.3 km perpendicular to the hillslope, from a wellpad to springs.

Even where vertical surface-to- groundwater pathways are not compromised, there are other aspects of SGD that may impact directly on surface resources, with potential knock-on effects in downstream areas and even external catchments, as well as on groundwater (dealt with in Subsection 5.5.1).

Those aspects linked primarily with surface water quality issues centre largely on **waste management and disposal**. Although this Chapter is not concerned with the actual processing and storage of waste (see Oelofse et al., 2016), it is concerned with the potential ultimate discharge of treated waste into watercourses or other surface water resources, the outcomes of illegal discharges of untreated waste into water resources and the potential for accidental spillage of contained waste in transit between wellpads and treatment plants. Hoffman et al. (2014) for example noted instances where tankers transporting waste leaked or overturned on roadways, resulting in discharges onto roadsides that were transported into watercourses, as well as cases of illegal dumping of waste into surface water bodies. Other waste-related impacts to surface waters revolve around their ultimate disposal and treatment, with reduction of TDS being a significant challenge face by Waste Water Treatment Facilities, while the alternative permanent storage of waste water may not be feasible in the long term.

Among the more contentious aspects of SGD in the Karoo region is the issue of **increased water demand** associated with these activities. Section 5.3.1 highlights the fact that surface water resources in the region are already generally over-utilised, with water being imported from the Orange River catchment to provide salinity-dilution services for irrigation in saline upstream areas as well as to supply urban and agricultural areas downstream and south of the study area (Figure 5.24). Given this, it is assumed that no additional surface water resources would be available to support the direct water requirements for SGD or alternatively, surface water resources could be targeted for such additional requirements only at the expense of existing users, including the environment.

This said, development, or even the perception of development of the industry may also prompt the migration of large numbers of job-seekers from major towns, as well as an increase in population numbers from actual employees engaged in the industry. While there is no legal imperative to supply water to meet the direct demands of the SGD industry, there is a requirement in terms of the NWA, to supply water to meet the basic human needs reserve. In the event of a major influx of people into a water scarce Karoo, there will be an increased demand for the provision of water as well as for the provision of sewage treatment and its discharge, either directly into watercourses or by way of irrigation of agricultural or other areas. Meeting such needs may compromise the capacity to meet either the Basic Human Needs or the Ecological Reserve, or both. The Reserve is already compromised in some areas (see Subsection 5.3.1) and potentially under further threat either in catchments within the study area or in catchments outside of the study area, such as the Orange River Catchment (see Subsection 5.3.2).

The previous concerns raised in this section have revolved around direct threats to surface water quality and quantity. **Landscape-scale disturbance** associated with SGD would potentially also impact on surface water resource condition, from exploration phase seismic activity assessments through to extensive road networks and their associated water course crossings, as well as to localised catchment hardening associated with site development. These activities all potentially contribute to increased flood peaks. In areas where the ratio of streamflow generated from large rainfall events is high (e.g. ratio of 1:50 to 1:10 year flood event for a 3 day storm – Figure 5.12), such impacts may significantly increase flooding and flood damage (e.g. erosion and downstream sedimentation). These have been described as common impacts associated with wellpad and pipeline construction in shale gas exploration and production (Brantley et al., 2014). It is noted however that flooding due to hardened surfaces would tend to be localised and can usually be easily mitigated by providing infrastructure.

Finally, the risk posed by SGD activities to **downstream dependent systems** including urban and agricultural users as well as environmental resources such as important estuaries is poorly understood and inadequately quantified. Figure 5.7 illustrates the catchments that are downstream of the present study area, and thus potentially in any surface contamination stream.

The following sections draw on the preceding discussion, in summarising impacts to surface water resources likely to be associated with various activities associated with SGD, and in terms of the scenarios described in Chapter 1 (Burns et al., 2016) in the Preface (Scholes et al., 2016). Mitigation measures are outlined where possible, with avoidance mitigation being highlighted as preferable with regard to a potentially high risk activity being carried out under conditions of (often) low levels of information and/or poor data quality.

5.5.3.2 Assessment of likely impacts resulting from SGD activities

Reference Case

At the outset, it is noted that the Reference Case does not entail any SGD. The Reference Case does, however take cognisance of likely climate change impacts, as well as impacts to surface water ecosystems namely ongoing and increasing water scarcity with climate change likely to result in an increased frequency of extreme events such as drought and floods (Burns et al., 2016). Figure 5A1.15 in Digital Addendum 5A) shows that, in a severe drought, 60% of the study area would receive less than 100 mm rainfall per year. Figure 5.26 shows moreover that in a climate change scenario, runoff would decrease over 80% of the study area, with decreases varying between 15% and 60% of Mean Total Streamflow. These are significant projected decreases, in an environment experiencing already stressed surface water resources. Assuming, as already described in Section 5.3, that fresh water resources are already limited in the study area and limit development, such limitations are likely to become more significant in the future.

Increased assignment of land to the development of renewable energy (e.g. solar power) could trigger catchment hardening and landscaping fragmentation, with concomitant impacts to surface water resources, although the anticipated large-scale influx of jobseekers and its associated likely significant increase in demand for water resources in the case of SGD is probably unlikely.

Direct impacts to surface water resources associated with the Exploration Only, and Small and Big Gas scenarios

Impact A: ***Degradation of watercourses as a result of physical disturbance during exploration.*** It is assumed that additional water demand during the exploration phase would be met through increased groundwater abstraction (see Subsection 5.5.1). **S**eismic exploration could however include disturbance to numerous watercourses and potentially pans and wetlands as well. Resultant compaction and surface disturbance both within watercourses and their catchments would potentially affect infiltration rates (e.g. in alluvial gravels and sands) and increase runoff rates across disturbed compacted surfaces. Such impacts would result in degradation in overall river condition, and where pans and other wetlands were affected by sedimentation and/or high runoff, would decrease the condition of these systems as well. While the biodiversity implications of these impacts are dealt with in Holness et al. (2016), general degradation of surface resource quality is relevant to the present assessment. A decrease in PES category could well result, particularly in rivers to the west of the study area, where high PES categories (A and B) are assumed to reflect low levels of physical disturbance in an arid landscape. The physical activities associated with seismic exploration would be short-lived in all scenarios – however, their effects would potentially be long-term, given the arid environment in which they occur and the slow associated rates of geomorphological recovery.

Mitigation: Mitigation would require avoidance of water courses and pans, and particular attention to disturbance avoidance and remediation in areas prone to extreme rainfall and associated (amplified) runoff (see Figure 5.12). The setbacks from surface water resources cited for Ancillary Activities in Table 5.10 (Subsection 5.7.3) should be implemented, to avoid such impacts.

Impact B: ***Contamination of surface water resources as a result of accidental flowback or production water discharge into surface systems or illegal discharge of waste into surface resources.*** Such impacts, including the accidental passage of saline waste into surface water systems could have significant negative impacts on surface water resource quality, as described in Subsection 5.5.1.1. The likelihood of accidental contaminant release as a result of flooding or storm events would be higher in areas associated with more severe flood events (e.g. as shown in Figure 5.12), and particularly along waste transport routes (e.g. overturning of waste transport trucks and the direct or indirect passage of waste into watercourses). However, since the origins of such incidents are often human error or malice, they are likely to occur outside of storm events as well.

Mitigation: Risk avoidance mitigation is recommended, and the setback areas from all surface water resource components listed in Table 5.10 must be implemented, as these setbacks serve to separate the resource from zones of potential contamination, including roads. In addition, Best Practice measures outlined in Subsections 5.7.1and 5.7.2 and Table 5.9 in particular, including both on-site bunding and in-transit bunding, must be included in all activities involving the storage, transport or other handling of contaminated waste.

Impact C: ***Contamination of surface resources as a result of contact with contaminated groundwater.*** In the event that such contamination occurred, and while a similar range of chemicals to that described in the case of accidental spillage or leaks from flowback water could be anticipated, the duration of exposure could be long-term and immitigable. Nevertheless, the likelihood of occurrence would be very low. The onset of such an impact might also only be at some time far into the future, and thus more difficult to identify.

Alternative pathways for the kinds of groundwater-to-surface water contamination would include active pumping of contaminated water via boreholes supplying reservoirs and dams, as well as degradation of well seals/liners in the long-term, which allow contaminated water to mix between aquifers. This is considered likely in the long term – that is, over timescales of up to hundreds of years.

Mitigation: Mitigation would need to take the form of avoidance of areas in which surface-groundwater linkages are likely (thus reducing vulnerability), and of enforced long-term (permanent) maintenance and management schedules for all wells, on a permanent basis after decommissioning. This means that sufficient long-term funding for such activities must be set aside in trust at the outset of any exploration phase involving deep aquifer penetration and/or fracking, regardless of the profitability of such ventures from a shale gas production perspective. The mitigation measures outlined for long-term groundwater protection are recommended for surface water protection, and include recommendations for high levels of assurance of long-term monitoring and maintenance interventions from the outset of SGD involving fracking. Possible mechanisms whereby this might be achieved would be via a long term, dedicated Trust Fund, or alternatively through insurance schemes covering long-term liabilities in case of catastrophic failure.

The setback areas recommended to ensure the protection of surface water resources outlined in Table 5.10 should be implemented, with areas outside of the mapped setbacks associated with the least risk of surface/groundwater impacts being incurred.

Impact D: **Changes in the characteristics of surface water resources as a result of imports of alternative water sources into the study area to meet drilling and fracking requirements**. Given that the surface resource is considered utilised to its full potential already, it is assumed that additional direct water demand during the exploration phase would be met through sources other than surface waters.

SSI (2012) identifies sea water, desalinated water and treated sewage as potential alternative water sources. Large volumes of these water sources would be required (Table 5.3 and 5.4) and, particularly in the Big Gas scenario where the density of operations would be high, it is possible that point source passage of waste water into surface water courses could occur. Depending on the quality of water used, such waste streams could include nutrient enrichment as well as increased salinities, both of which would degrade surface water resources, if they entered as waste streams or accidentally through spills, overflows or leakages.

Mitigation: Avoidance of ecologically important watercourses or watercourses upstream of catchments with high sensitivity to increased nutrients or salinisation, depending on the source of water, would be required. Detailed assessments of any proposed imports of water resources into the study area would be required to inform adequate mitigation and/or avoidance of significant negative impacts.

Indirect impacts to surface water resources associated with the Exploration Only, and Small and Big Gas scenarios

It is likely that SGD in the study area would have indirect impacts on water resources at a regional level, as a result of the likely associated influx of additional people into the area. The magnitude of such impacts would increase between the Exploration Only and Big Gas scenarios. Three main indirect impacts are considered here.

Impact A: **Changes in surface resource characteristics and stresses as a result of population influxes into water scarce towns and an associated requirement in terms of the NWA for the provision of adequate water to meet their basic water requirements, as well as the reality that actual water demands by an increasing population are likely in practice to exceed such volumes**. It is assumed that increased water demand would need to be met by sourcing alternative water supplies. Since South Africa is already a water-stressed country, the indirect environmental and developmental opportunity costs of sourcing such water would need to be considered, including the ecological costs of enabling activities such as the construction of additional dams on the Orange River, as already discussed in NWRS (2013).

Mitigation: Mitigation would need to consider proposed approaches at a strategic and then detailed impact assessment level. The risks associated with this impact are not therefore assessed in this study "with mitigation".

Impact B: **Changes in surface resource characteristics and stresses as a result of increases in requirements for sewage treatment and effluent discharge, as a result of population increases.** In the event that effluents, possibly with a high salt content if influenced by SGD brines as well, were discharged into watercourses, there would be possible changes in instream hydro-period at least locally, resulting in changes in plant and faunal composition along these systems, which might in turn affect resource quality. Given the scarcity of water resources in the study area, and the likelihood that this will be exacerbated over time as a result of climate change, such discharge into surface water systems is however considered unlikely, given the availability of alternative uses for effluent such as for irrigation. However, if short-term storage and conveyance relied on the use of storage dams and in-channel conveyance, then significant changes might occur, particularly if the use of nutrient enriched or saline water was considered.

In the event that insufficient facilities were available for the treatment of increased sewage loads to adequate standards, then bacterial contamination and significant degradation of affected surface resources could occur, including possible permanent salinisation of soils in affected watercourses as a result of inadequate treatment to remove brine.

Mitigation: Mitigation would need to be at a strategic level – while obvious forms of mitigation would include allowance for adequate waste treatment, for both direct SGD-derived waste (e.g. brines) and indirect waste (e.g. sewage), and its beneficial reuse (ideally) or its alternative benign disposal so as not to disrupt natural surface water ecosystems, allowance for such facilities would need to be undertaken at a Municipal level, rather than by individual developers. Long-term strategic interventions would thus need to be undertaken timeously, and not simply at the start of SGD activities. The disposal of sewage effluent would, in particular, need to avoid disrupting the natural seasonality of Karoo watercourses.

Given the complexity of mitigation at a strategic level and the number of unknowns at this stage, the risks associated with this impact have not been assessed in this study "with mitigation".

Impact C: **Increased peak discharges and associated erosion and watercourse degradation from increased road crossings and catchment hardening**. An inevitable consequence of the kind of activities associated with the proposed exploration, appraisal and production phases of SGD in a largely undeveloped region such as the Karoo is that additional infrastructural development requirements would be high, including the need for roads, pipelines, and possibly other service infrastructure such as electricity and communication networks (e.g. fibre-optic cables etc.). At a large-scale (e.g. Big Gas scenario) such activities would entail multiple and permanent changes at a landscape level, affecting watercourses by fragmentation (multiple crossings), which increase the risk of flood-event driven damage such as erosion, which usually concentrates at road crossings. Such impacts are, it is assumed, also assessed in Holness et al. (2016).

Mitigation: While mitigation of the above would be possible to some degree, such impacts would be an inevitable component of extensive development, and would contribute to potential lowering of presently high PES categories for rivers across affected parts of the study area.

Nevertheless, the setback areas recommended to ensure the protection of surface water resources outlined in Table 5.10 for "Ancillary Activities" should be implemented, with areas outside of the mapped setbacks associated with the least risk of surface/groundwater impacts being incurred.

Impact D: **Failure of mitigation and best practice measures as a result of poor institutional capacity and/or will to effect compliance with legislation and required conditions of authorisation.** This is considered a high risk in South Africa's current climate, where the water resources sector is often characterised by a lack of institutional capacity, poor levels of experience and training amongst implementing officials, a limited capacity to undertake effective audits, poor training in and ability to implement existing legislation, and poor records in effecting visible and consistent application of legislation.

Mitigation: Mitigation requires a significant *a priori* investment into the water resources and affiliated sectors, around ensuring high standards in setting legally defendable licensing conditions for SGD, ensuring adequate collection of pre-impact baseline data, effective policing of developer and State compliance in both the short- and the long-term, and ensuring that monitoring is carried out in a scientifically and technically rigorous manner, with sound interpretation of results and their implications, and adequate allowance for effective interventions in the event of critical thresholds being approached (see Section 5.6).

5.6 Risk Assessment

5.6.1 Identification of sensitive areas

Assessment of the risks to ground- and surface water resources as a result of both direct and indirect impacts derived from SGD and associated activities has been based on the methodology and assumptions outlined in the Preface to this scientific assessment (Scholes et al., 2016). In order to provide a spatial representation of the study area in terms of Risk, two approaches were followed.

- First, Figure 5.12 was used as the basis on which to assign levels of risk in the placement of SGD within the study area – Quinary catchments in which the ratio of the 1:50 to 1:10 year extreme 3 day streamflow event is >3 are considered to be **High Risk areas** for undertaking any of the activities associated with SGD, given the severe levels of external disturbance to which they are likely to be exposed over the life of the development, increasing the probability of resource contamination and other sources of degradation.

- Secondly, the setbacks developed during the course of this scientific assessment (see Section 5.7.3) and detailed in Table 5.10, were applied to all aspects of geology, geohydrology and surface water resources considered necessary to assure the protection of water resources in a SGD context. The mitigation measures outlined in Section 5.5 and assumed in the assignment of risk ratings "with mitigation" (Table 5.5 and 5.6) are based largely on achieving these setbacks. The setbacks themselves do not necessarily represent areas of certain high sensitivity. Rather, in a field with high levels of uncertainty, they have been developed to exclude areas where SGD activities could pose a risk to the resource, and thus indicate areas where there is at least moderate confidence that SGD activities could proceed without incurring such risk. In some instances, further investigation within the setback areas might show less actual risk than that based on small-scale maps and coarse data, and such refinement might indicate additional areas for development.

At the level of the current assessment, a conservative, risk-averse approach is however considered warranted. Two sets of maps were developed through this process. They are shown as summary overlays in Figure 5.28 to 5.31, but detailed in Digital Addendum 5E, allowing the contribution of individual criteria to overall setback definition to be gauged. The figures indicate (separately) setbacks that should be applied in siting any activities involving fracking, and those that must be applied in the siting of so-called "Ancillary Activities" – that is, all other activities and infrastructure that do not include fracking. In this regard, it must be stressed that Figure 5.28 to 5.31 showing areas of particular significance with regard to surface and groundwater resources, have been mapped mostly at a small scale (e.g. 1:500 000), and actual site-specific conditions within various categories of classification are liable to vary quite widely. These figures must therefore be interpreted strictly with this limitation in mind.

5.6.2 *How are risks measured?*

The determination of risk in this scientific assessment was derived from a matrix of the likelihood of occurrence and the consequences if a particular event occurred. This matrix is presented in the Preface (Scholes et al., 2016), and is common to all of the risk assessments presented in the different Chapters of the scientific assessment. Different levels of certainty encompassed in the likelihood ratings have also been clearly defined in the Preface Scholes et al. (2016). By contrast, the levels of consequence that are used in the risk matrix require calibration and/or definition with regard to Surface and Groundwater Resources. The definitions developed for the purposes of this Chapter are outlined in Table 5.5, where:

- **Duration** is categorised as short-, medium- and long-term, as follows:
    - Short-term (<3 years)
    - Medium-term (3 to 40 years)
    - Long-term (>40 years and in some cases extending hundreds of years into the future)
- **Extent** is categorised as Local/site specific, Medium and Regional, as follows:
    - Local/site specific (defined as local/site specific for surface water resources and occurring at a local level and/or the level of a wellpad for groundwater resources);
    - Medium (occurring within a defined reach level/Quaternary catchment(s)/pan or wetland cluster or system for surface water resources and at the level of a groundwater system of aquifer for groundwater resources);
    - Regional (occurring at a catchment scale or across catchments (that is, upstream/downstream longitudinally at a catchment level (primary river) and/or adjacent primary or secondary catchments for surface water resources and at a trans-system/trans-basinal scale for groundwater resources).

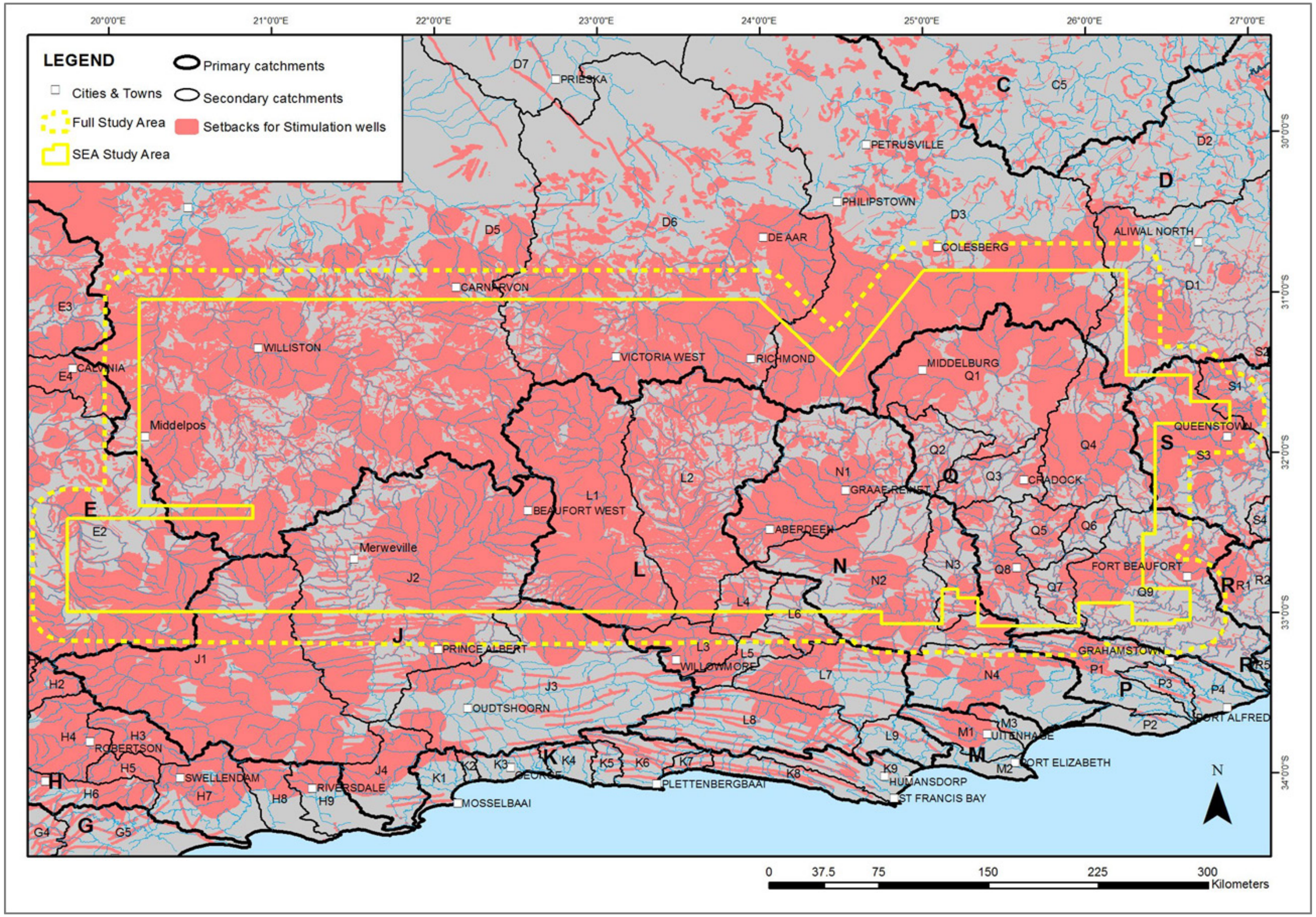

Figure 5.28: Combined sensitivity map for stimulation well activities.

In the grey areas (medium sensitivity) well stimulation (fracking) activities might take place with at least medium confidence (given concerns regarding scale of mapping) that it will not impact significantly on known surface and/or groundwater resources. Highlighted pink areas of high sensitivity comprise areas in which impacts to water resources is possible, and if so, might have highly negative consequences. The figure must be interpreted in the light of known mapping constraints, with particular regard scale (some features mapped at a very small scale, while setbacks defined at a very fine scale). In addition, dolerite dykes have been accorded a minimum sensitivity of 250 m which might not always apply - dolerite dyke spatial data require better resolution than at present. Sensitivity shown here is determined from setback distances recommended in Table 5.10. Note: Not all features in this table are represented in this figure, only features for which spatial data was available at the time.

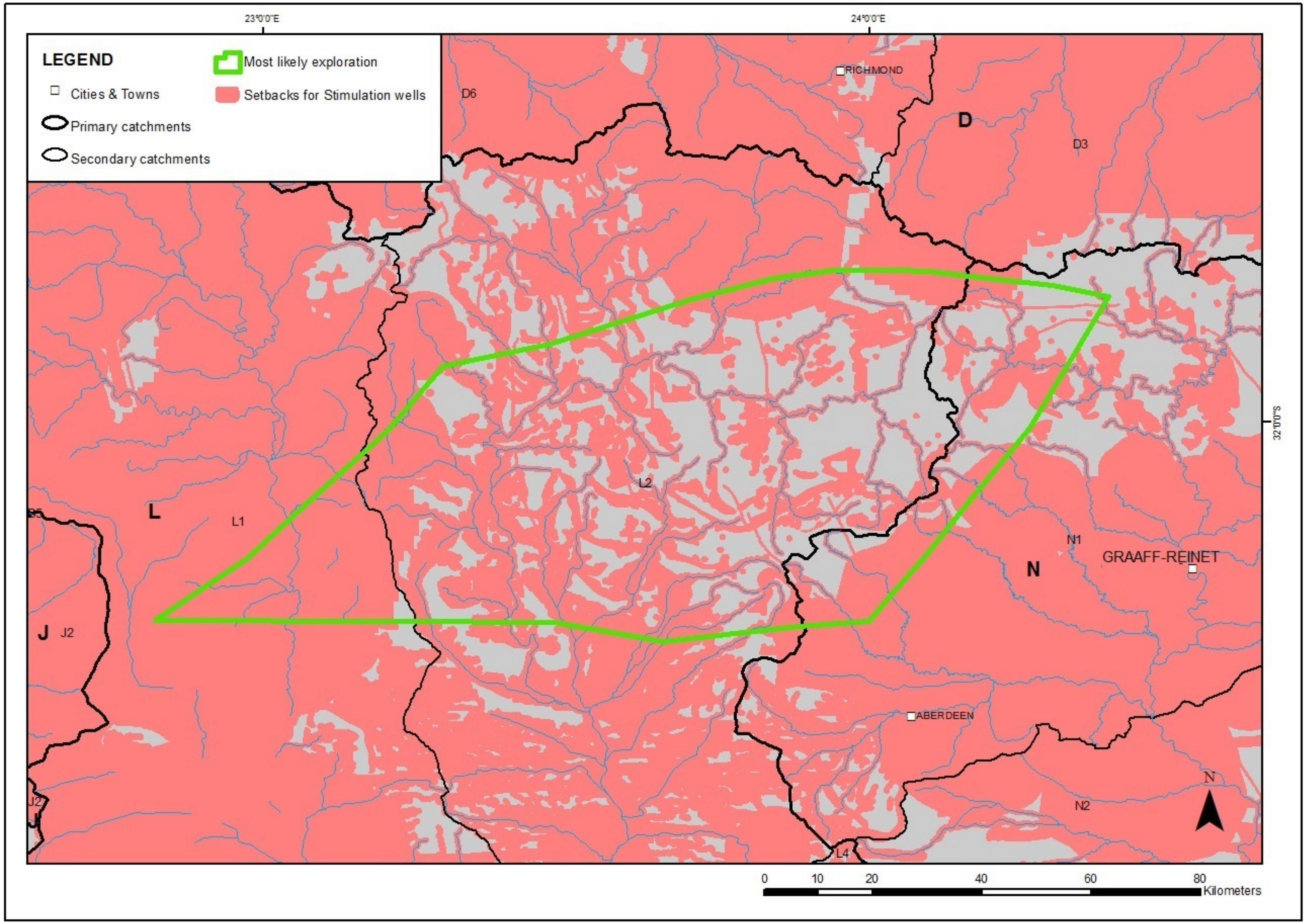

Figure 5.29: Combined sensitivity for stimulation well activities: focus on assumed most likely exploration zone, to illustrate high sensitivity areas at a larger scale than in Figure 5.28.

Map showing medium sensitivity areas (grey) in which well stimulation (fracking) activities might take place with at least medium confidence (given concerns regarding scale of mapping) that it will not impact significantly on known surface and/or groundwater resources. Highlighted (pink) high sensitivity areas comprise those areas in which some risk to water resources is potentially possible, and if so, might have highly negative consequences. The figure must be interpreted in the light of known mapping constraints, with particular regard to those of mapping scale (some features mapped at a very small scale, while setbacks defined at a very fine scale). In addition, dolerite dykes have been accorded a minimum setback of 250 m which might not always apply dolerite dyke spatial data require better resolution than at present. Setbacks shown here illustrate the combined setback distances recommended in Table 5.10. Note: Not all features in this table are represented in this figure, only features for which spatial data was available at the time of compilation of this Chapter, are shown.

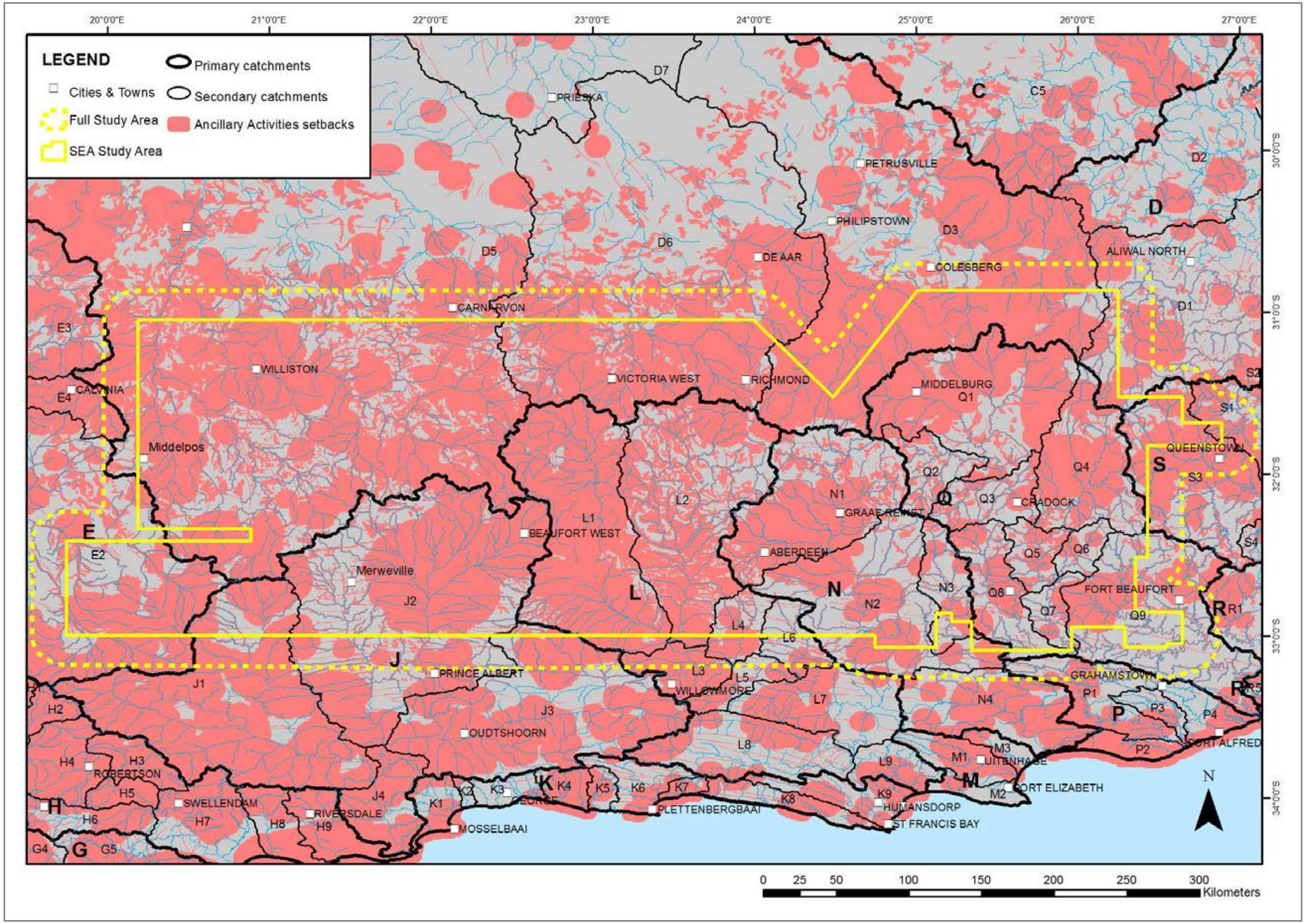

Figure 5.30: Combined sensitivity for so-called “Ancillary Activities” (as defined in Table 5.10).

Map showing remaining grey areas (medium sensitivity) in which ancillary activities might take place with at least medium confidence (given concerns regarding scale of mapping) that it will not impact significantly on known surface and/or groundwater resources. Highlighted pink areas of high sensitivity comprise those areas in which some risk to water resources is possible, and if so, might have highly negative consequences. The figure must be interpreted in the light of known mapping constraints, with particular regard to those of mapping scale (some features mapped at a very small scale, while setbacks defined at a very fine scale). In addition, dolerite dykes have been accorded a minimum setback of 250 m which might not always apply – dolerite dyke spatial data require better resolution than at present. Setbacks shown here illustrate the combined setback distances recommended in Table 5.10. Note: Not all features in this table are represented in this figure, only features for which spatial data were available at the time of compilation of this Chapter, are shown.

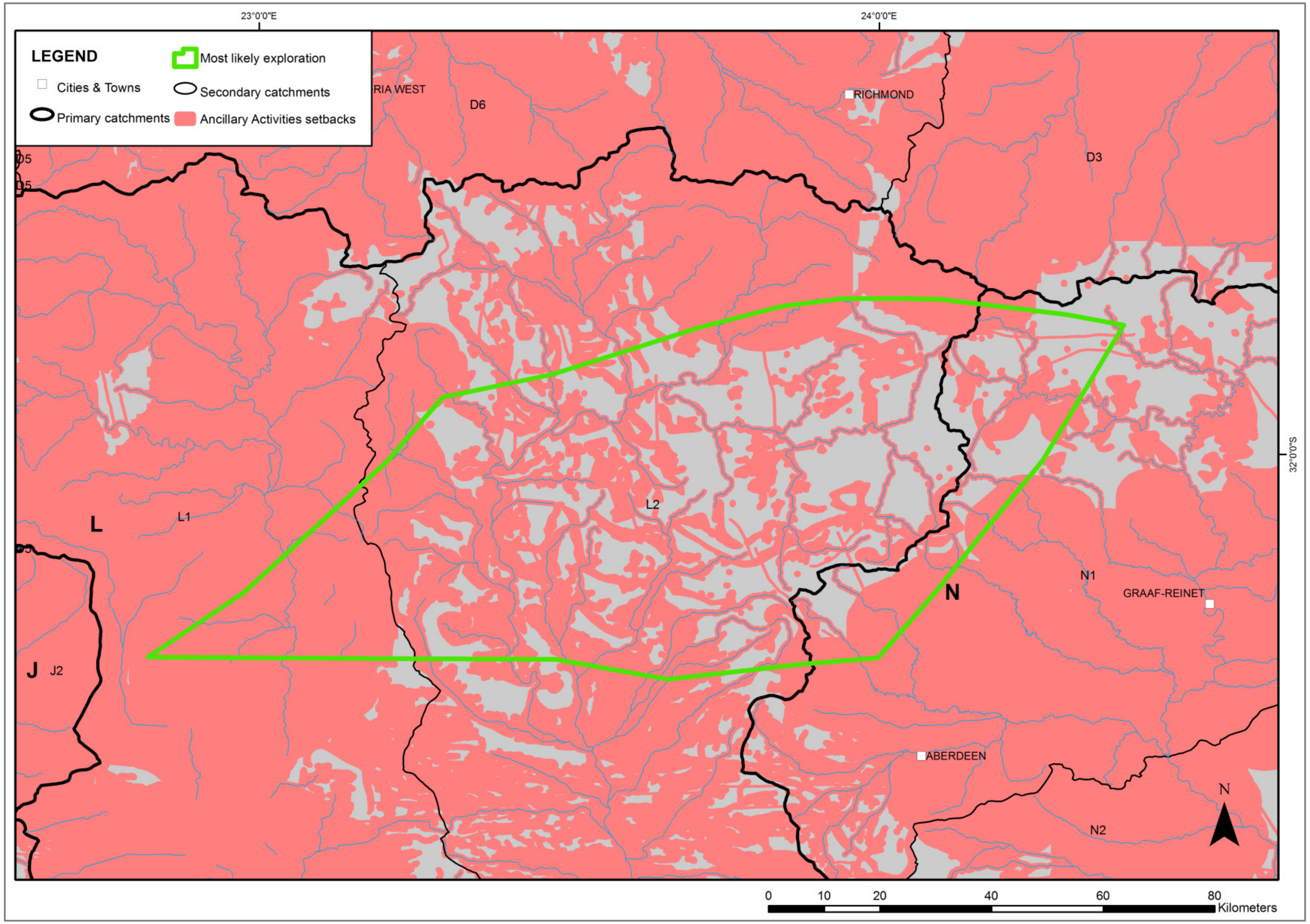

Figure 5.31: Combined sensitivity for so-called "Ancillary Activities" (as defined in Table 5.10): focus on assumed most likely exploration zone, to illustrate setbacks at a larger scale than in Figure 5.30.

Map showing grey areas (medium sensitivity) in which ancillary activities might take place without impacting significantly on known surface and/or groundwater resources. Highlighted (pink) areas comprise high sensitivity areas in which some risk to water resources is possible, and if so, might have highly negative consequences. The figure must be interpreted in the light of known mapping constraints, with particular regard to those of mapping scale (some features mapped at a very small scale, while setbacks defined at a very fine scale). In addition, dolerite dykes have been accorded a minimum setback of 250 m which might not always apply - dolerite dyke spatial data require better resolution than at present. The sensitivities shown here illustrate the combined setback distances recommended in Table 5.10. Note: Not all features in this table are represented in this figure, only features for which spatial data was available at the time of compilation of this Chapter, are shown.

Table 5.5: Consequence levels developed for use in assignment of risk to water resources.

<table>
<tr><th>Consequence Level</th><th>Description</th></tr>
<tr><td>Slight</td><td>Impacts reduce risk or do not change it in a way that is discernible
No thresholds of concern[3] (see Box for definition) are exceeded
Resource ecostatus class would not change
Limited in extent: Site specific
Readily reversible at any time and/or of short-term duration</td></tr>
<tr><td colspan="2">The impact should not have an influence on the decision, provided that recommended measures to mitigate negative impacts are implemented.
A slight consequence level would be accorded to the following ratings:
• EITHER of low intensity at a local extent and endure in the medium-term;
• OR of low intensity with medium extent and endure in the short-term;
• OR of low to medium intensity at a local extent and endure in the short-term</td></tr>
<tr><td>Moderate</td><td>Some degradation in resource status/possible change in class
Thresholds of concern may be exceeded
Readily reversible once activity ceased
Impacts will be well within the tolerance levels or adaptive capacity of the users (NWA) relying on the resource</td></tr>
<tr><td colspan="2">The impact should not have an influence on, or require to be significantly accommodated in the development design.
A moderate consequence level would result from the following categories of impacts:
• EITHER of low intensity at a medium extent and endure in the medium-term;
• OR of high intensity at a local extent and endure in the short-term;
• OR of medium intensity at a regional extent in the short-term;
• OR of low intensity at a local extent and endure in the long-term;
• OR of medium intensity at a local extent in the short-term (excluding cumulative impacts);</td></tr>
<tr><td>Substantial</td><td>Marked degradation in resource status
Thresholds of concern are exceeded
Surface water impacts potentially reversible once activity ceases
Groundwater impacts reversible only with significant human intervention over decades
Beyond the adaptive capacity of the users relying on the resource</td></tr>
<tr><td colspan="2">The impact could have an influence on the environment which will require modification of the development design or alternative mitigation.</td></tr>
</table>

[3] Thresholds of Concern (usually referred to as Thresholds of Potential Concern (TPCs) or Stress Tipping Points) are numerically defendable nodes after which damage to ecosystems is expected to be irreversible (Rogers and Bestbier, 1997). Such thresholds would need to be defined for the variables of concern in a SGD scenario.

<table>
<tr><th>Consequence Level</th><th>Description</th></tr>
<tr><td colspan="2">A substantial consequence level would result from the following categories of impacts:
• EITHER of high intensity at a local level and endure in the medium-term;
• OR medium intensity at a medium level in the medium-term;
• OR of high intensity at a medium level in the short-term;
• OR of medium intensity at a regional level and endure in the short-term;
• OR of medium intensity at a local level and endure in the long-term;
• OR of low intensity at a regional level in the medium-term;
• OR of low intensity at a medium level in the long-term</td></tr>
<tr><td>Severe</td><td>Considerable degradation in resource status
Thresholds of concern significantly exceeded, approaching system-state tipping point
Surface water impacts reversible only with human intervention over decades
Groundwater impacts are effectively irreversible</td></tr>
<tr><td colspan="2">The impact could have a no-go implication for the development or a component of the development, regardless of any possible mitigation).
A severe level of consequence would result from the following categories of impact:
• EITHER of medium intensity at a medium extent in the medium-term;
• OR of high intensity at a regional extent in the short-term;
• OR of medium intensity at a regional extent in the medium-term;
• OR of low intensity at a regional extent in the long-term;
• OR of high intensity at a local extent in the long-term;
• OR of medium intensity at a medium extent in the long-term</td></tr>
<tr><td>Extreme</td><td>Significant degradation in resource status
Thresholds of concern are exceeded beyond critical system-state tipping point/irreversible change
Resource impacts irreversible and remediation impractical
Sole source groundwater resource that would be rendered unusable</td></tr>
<tr><td colspan="2">The impact would strongly influence the decision and further steps should be investigated to avoid the impact).
An extreme consequence level would result from the following categories of impact:
• EITHER of high intensity at a medium extent and endure in the medium-term;
• OR of high intensity at a regional extent in the medium-term;
• OR of medium intensity at a regional extent in the long-term</td></tr>
</table>

5.6.2 Defining limits of acceptable change

The limits of acceptable change in different aspects of surface and groundwater resources, as considered in this Chapter, refers to the degree to which some change in resource characteristics as a result of direct or indirect impacts of SGD may be acceptable from a resource sustainability perspective. Beyond a certain point (limit or threshold), the impacts are likely to exceed sustainability levels.

The following "limits of acceptable change" are put forward in this scientific assessment:

- Any impact that would result in degradation of any aspect of the resource to a level less than the Desired Management Class for that resource component – note that the Desired Management Class has not yet been set for the study area, and would need to be set before any SGD-associated resource use is considered in this area;
- Any impact that results in a deterioration in resource quality would be an impact of high negative significance – even if associated with only one attribute or one water quality variable. The water quality guidelines for aquatic ecosystems and agriculture, as listed in Table 5.6, should be used as a guide to what constitutes a significant change in a water quality variable, bearing in mind that pre-SGD conditions might already exceed some of these thresholds. This emphasises the importance of undertaking extensive pre-development monitoring (see Section 5.8).

Management Class and the Water Resource Classification System (WRCS)

(after Dollar et al., 2006)

The WRCS is a set of guidelines and procedures for determining the different classes of water resources.

The Management Class (MC) represents the desired characteristics of the resource and outlines those attributes that the custodian (DWS) and society require of different water resources. The outcome of the Classification Process will be the setting of the Management Class, Reserve and Resource Quality Objectives (RQO's) for every significant water resource. The aim of this process is therefore to help facilitate a balance between protection and use of the nation's water resources. The WRCS is required by the National Water Act (NWA) (No. 36 of 1998 (Chapter 3, Part 1, Section 2(a)).

Table 5.6: Target water quality ranges for surface water use, with values taken from DWAF (1996a, b and c) unless otherwise specified. Concentrations are of dissolved, usually ionic, species of the elements listed. [ ] = concentration.

Chemical substance or Physical property	**DWAF target water quality range for irrigation (after DWAF, 1996a)**	**DWAF target water quality range for stock watering (after DWAF, 1996b)**	**DWAF Target Water Quality Range for aquatic ecosystems (after DWAF, 1996c)**	**Acute toxicity values and comments (after DWAF, 1996c unless specified otherwise)**
Electrical conductivity (mS/m) (=TDS)	≤40	≤300	TDS concentrations should not vary by >15% from normal cycles in the water body at any time of the year and the amplitude and frequency of natural cycles in [TDS] should not change.	
pH	6.5-8.4		pH should not vary from the range of background pH values for a specific site and time of day by >0.5 of a pH unit or by >5%, whichever is the more conservative. [nb: pH values in natural waters in the south-western Cape may be as low as 4.0 because of the presence of humic substances.]	
Suspended solids (mg/L)	≤50		Increases should be <10% of background [TSS] at a specific site and time. This criterion refers only to the physical presence of particulate material and not any potential toxic effects.	
Temperature			Species and site-dependent: should not vary from natural conditions for the specific site and time of day by >2°C.	
Aluminium (mg/L)	≤5.0	≤5.0	pH ≤6.5, 0.005	pH ≤6.5, 0.1 (DWAF (1996C)); pH ≤6.5, 0.75 (EPA) Aluminium is extremely toxic at low pH values (<6) and is the prime cause of biodiversity loss in acidified water
Ammonia (mg/L)			≤0.007 mg/l un-ionised ammonia (i.e. NH_3, pH >8.4)	0.1 mg/L un-ionised ammonia (i.e. NH_3, pH >8.4) (DWAF, 1996C); 2.9 mg/L N: EPA https://www.regulations.gov/document?d=epa-hq-ow-2009-0921-0001 Ammonia (NH_3) is very toxic but ionised ammonium ions (NH_4^+) are not.
Arsenic (mg/L)	≤0.1	≤1	≤0.01	0.13 (DWAF (1996C)); 0.34 (EPA) Arsenic is toxic and carcinogenic.
Beryllium (mg/L)	≤0.1 mg/L			Beryllium is extremely toxic but is found in natural waters only at very low concentrations.
Boron (mg/L)	≤0.5	≤5.0		Although boron is an essential plant nutrient, many of its compounds are toxic to plants at relatively low concentrations
Cadmium (mg/L)	≤0.01	≤0.01	**≤0.00015-0.00040	**0.003-0.013 Cadmium is toxic at very low concentrations; it can accumulate in plants and soils, making them toxic too.
Chlorine, free (mg/L)			≤0.0002	0.013 (EPA) While chloride ions (Cl^-) are not toxic, free chlorine (Cl_2, HOCl) is extremely toxic.
Chromium (vi) (mg/L)	≤0.1	≤1	≤0.007 Cr(vi)	0.200 (DWAF, 1996C); 0.016 (EPA)

Chemical substance or Physical property	DWAF target water quality range for irrigation (after DWAF, 1996a)	DWAF target water quality range for stock watering (after DWAF, 1996b)	DWAF Target Water Quality Range for aquatic ecosystems (after DWAF, 1996c)	Acute toxicity values and comments (after DWAF, 1996c unless specified otherwise)
			≤0.012 Cr(iii)	The chemical species of chromium vary in toxicity, the highly oxidised Cr (vi) being most toxic.
Cobalt (mg/L)	≤0.05	≤1		**0.34-1.0 (Diamond et al., 1992) Cobalt is toxic at low concentrations but more so in soft than hard waters.
Copper (mg/L)	≤0.2	≤0.5	**≤0.0003 –0.0014	**0.0016-0.012 Copper is a micronutrient but is toxic even at low concentrations. It is commonly used to suppress algal growth.
Cadmium (mg/L)			**0.15-0.4	**0.003-0.013 (DWAF, 1996c); 0.002 (EPA) Cadmiumd is potentially harmful to most forms of life (EPA)
Cyanide (mg/L)			≤0.001	0.110 (DWAF, 1996c); 0.022 (EPA)
Fluoride(mg/L)	≤2	≤2	≤0.750	2.540 While fluoride is necessary for bones and teeth of vertebrates, it is toxic at fairly low concentrations
Iron (mg/L)	≤5	≤10	Concentrations should not vary by >10% of the background concentration at a specific site and time	
Lead (mg/L)	≤0.2	≤0.1	**≤0.0002 – 0.0012	**0.004 – 0.016 (DWAF, 1996C), 0.065 (EPA) Lead is a very toxic element.
Manganese (mg/L)	≤0.02	≤10	0.180	1.300 Manganese is more toxic at low than at high pH values
Mercury (mg/L)		≤0.001	≤0.00004	0.0017 (DWAF, 1996c); 0.001(EPA) - both methyl mercury. Mercury, especially in the form of methyl mercury, is extremely toxic
Nickel (mg/L)	≤0.2	≤1		**0.47 (EPA) Nickel is toxic and carcinogenic.
Nitrate/nitrite as N (mg/L)	≤5	≤100		Nitrates and nitrites are not normally directly toxic in the aquatic environment
Phosphorus (as orthophosphate (mg/L)			Inorganic phosphorus concentrations should not be changed by >15% from that of the water body under local, un-impacted conditions.	
Selenium (mg/L)	≤0.02	≤50 micrograms	≤0.002	0.030 (DWAF, 1996c); 0.005 (EPA: https://www.epa.gov/sites/production/files/2016-06/documents/se_2016_fact_sheet_final.pdf) Selenium is a micronutrient but is toxic at higher concentrations; it also accumulates up the food-chain.
Uranium (mg/L)	≤0.01			As well as radiation effects, uranium is known to be toxic to humans and,

Chemical substance or Physical property	DWAF target water quality range for irrigation (after DWAF, 1996a)	DWAF target water quality range for stock watering (after DWAF, 1996b)	DWAF Target Water Quality Range for aquatic ecosystems (after DWAF, 1996c)	Acute toxicity values and comments (after DWAF, 1996c unless specified otherwise)
				by implication, to many other living organisms
Vanadium (mg/L)	≤0.1	≤1		Vanadium is accumulated by some marine organisms but is toxic to most organisms at relatively low concentrations.
Zinc (mg/L)	≤1	≤20	≤0.002	0.036 (DWAF, 1996c); 0.120 (EPA) Zinc is an essential micronutrient but is also toxic at fairly low concentrations in the environment.

** Dependent on hardness of water: range from soft to hard water

EPA data from national recommended water quality criteria - aquatic life criteria table, https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table#a, updated 28.07.2016. Aquatic life criteria for toxic chemicals are "the highest concentration of specific pollutants or parameters in water that are not expected to pose a significant risk to the majority of species in a given environment".

Exact chronic effect values vary from species to species, so DWAF (1996c) and EPA values listed under "acute toxicity values" are not identical because they are based on toxicological experiments with different species, or include a "safety factor" where insufficient data are available. The values for each element are nonetheless usually well within the same order of magnitude.

Concentrations of the divalent cations Ca^{2+} and Mg^{2+} are low in "soft" waters and high in "hard" waters.

5.6.3 Results of Risk Assessment

The outcomes of the Risk Assessments are presented in the following tables. [Note: The tables have deliberately not been allowed to break across pages in order to facilitate the reading thereof.]

Table 5.7: Groundwater risk assessment

Note that assessments "with mitigation" in all cases included the assumption that SGD occurs outside of high sensitivity areas shown in Figure 5.28.

Direct impact	Scenario	Location	*Without mitigation*			*With mitigation (incl. avoidance of high sensitivity areas)*		
			Consequence	**Likelihood**	**Risk**	**Consequence**	**Likelihood**	**Risk**
Reduced water availability for people and other economic activities	Reference Case	In vicinity of wellfield or region where water is sourced	Moderate	Likely	Low	Moderate	Not likely	Low
	Exploration Only		Moderate	Likely	Moderate	Slight	Likely	Low
	Small Gas		Severe	Likely	High	Substantial	Likely	High
	Big Gas		Extreme	Very likely	Very high	Severe	Likely	High
Contamination of groundwater resources through surface spills and discharge	Reference Case	High sensitivity	Slight	Extremely unlikely	Very Low	Slight	Extremely unlikely	Very Low
	Exploration Only		Moderate	Likely	Low	Moderate	Not likely	Low
	Small Gas		Moderate	Likely	Low	Moderate	Not likely	Low
	Big Gas		Moderate	Likely	Moderate	Moderate	Not likely	Low
	Reference Case	Medium sensitivity	Slight	Extremely unlikely	Very low	Slight	Extremely unlikely	Very low
	Exploration Only		Moderate	Likely	Low	Slight	Extremely unlikely	Very low
	Small Gas		Moderate	Likely	Low	Moderate	Likely	Low
	Big Gas		Moderate	Likely	Low	Moderate	Likely	Low
Contamination of groundwater resources caused by a loss of well integrity and via preferential pathways caused by fracking	Reference Case	High sensitivity	Slight	Extremely unlikely	Very low	Slight	Extremely unlikely	Very low
	Exploration Only		Moderate	Likely	Low	Moderate	Not likely	Low
	Small Gas		Moderate	Likely	Low	Moderate	Likely	Low
	Big Gas		Substantial	Very likely	Moderate	Substantial	Likely	Moderate
	Reference Case	Medium sensitivity	Slight	Extremely unlikely	Very low	Slight	Extremely unlikely	Very low
	Exploration Only		Slight	Extremely unlikely	Very low	Slight	Extremely unlikely	Very low
	Small Gas		Slight	Extremely unlikely	Very low	Slight	Extremely unlikely	Very low
	Big Gas		Moderate	Likely	Low	Slight	Extremely unlikely	Very low

Figures 5.32 to 5.33 present risk maps of contamination of groundwater across four SGD scenarios, with- and without mitigation.

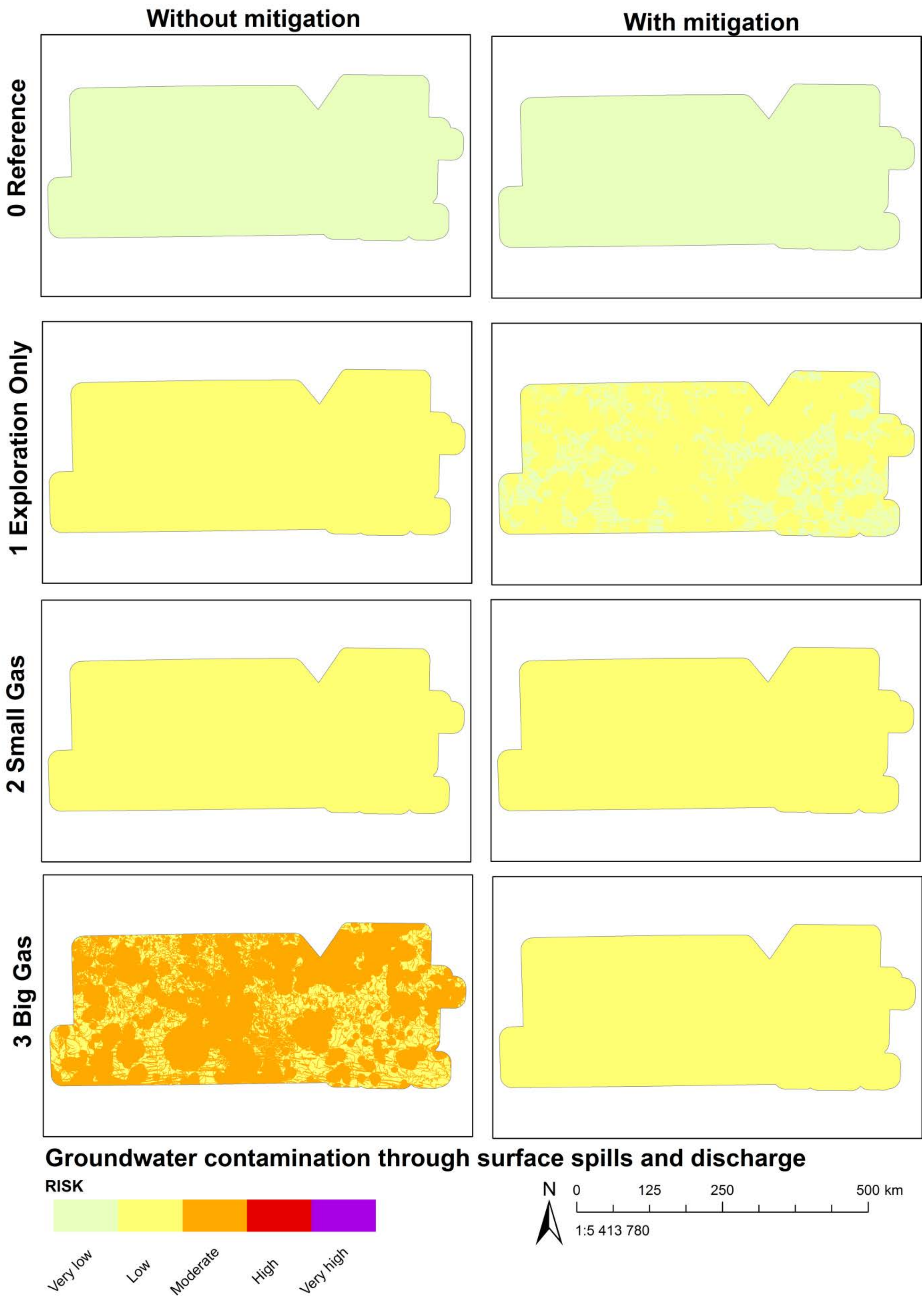

Figure 5.32: Map indicating the risk of groundwater contamination through surface spills and discharge across four SGD scenarios, with- and without mitigation.

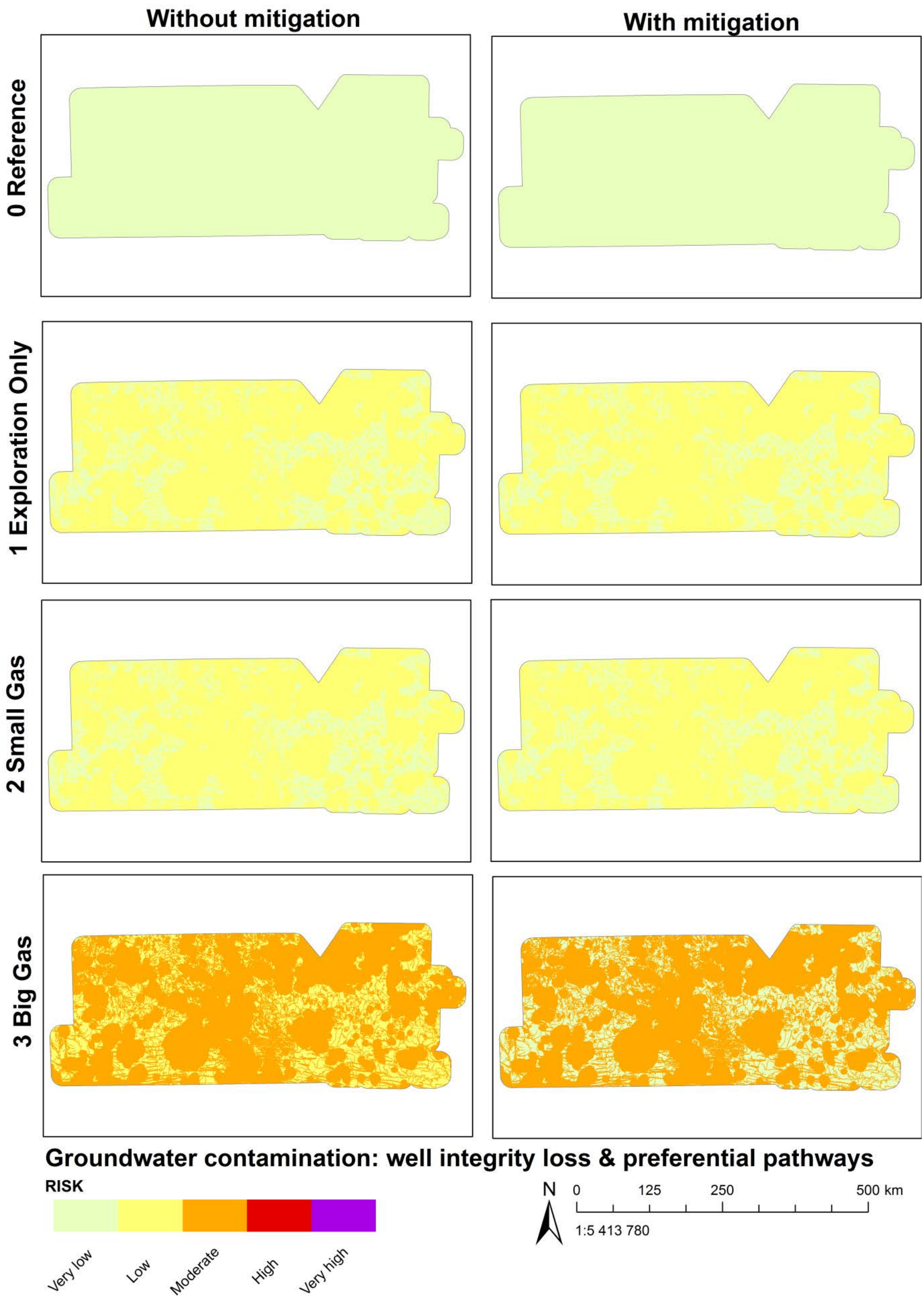

Figure 5.33: Map indicating the risk of groundwater contamination through the loss of well integrity and preferential pathways caused by fracking across four SGD scenarios, with- and without mitigation.

Table 5.8a: Surface water risk assessment of direct impacts.

Note that assessments "with mitigation" in all cases included the assumption that SGD occurs outside of high sensitivity areas shown in Figure 5.28.

Direct impact	**Scenario**	**Location**	***Without mitigation***			***With mitigation (incl. avoidance of high sensitivity areas)***		
			Consequence	**Likelihood**	**Risk**	**Consequence**	**Likelihood**	**Risk**
Physical disturbance to watercourses and contamination of surface water resources through flowback discharge and contact with contaminated groundwater	Reference Case	High sensitivity	Slight	Not likely	Low	Slight	Extremely unlikely	Very low
	Exploration Only		Moderate	Very likely	Moderate	Slight	Likely	Low
	Small Gas		Severe	Very likely	High	Moderate	Likely	Moderate
	Big Gas		Severe	Very likely	High	Moderate	Likely	Moderate
	Reference Case	Medium sensitivity	Slight	Extremely unlikely	Very low	Slight	Extremely unlikely	Very low
	Exploration Only		Slight	Not likely	Low	Slight	Extremely unlikely	Very low
	Small Gas		Moderate	Likely	Moderate	Slight	Not likely	Low
	Big Gas		Moderate	Likely	Moderate	Slight	Not likely	Low
Changes in the characteristics of surface water resources as a result of imports of alternative water sources into the study area to meet drilling and fracking requirements	Reference Case	Extensive within and potentially downstream of areas developed for SGD areas	Slight	Not likely	Low	Slight	Extremely unlikely	Very low
	Exploration Only		Slight	Not likely	Low	Slight	Not likely	Low
	Small Gas		Moderate	Not likely	Low	Moderate	Not likely	Low
	Big Gas		Moderate	Not likely	Low	Moderate	Not likely	Low

Figures 5.34 present risk maps of physical disturbance to watercourses and contamination of surface water resources through flowback discharge and contact with contaminated groundwater across four SGD scenarios, with- and without mitigation.

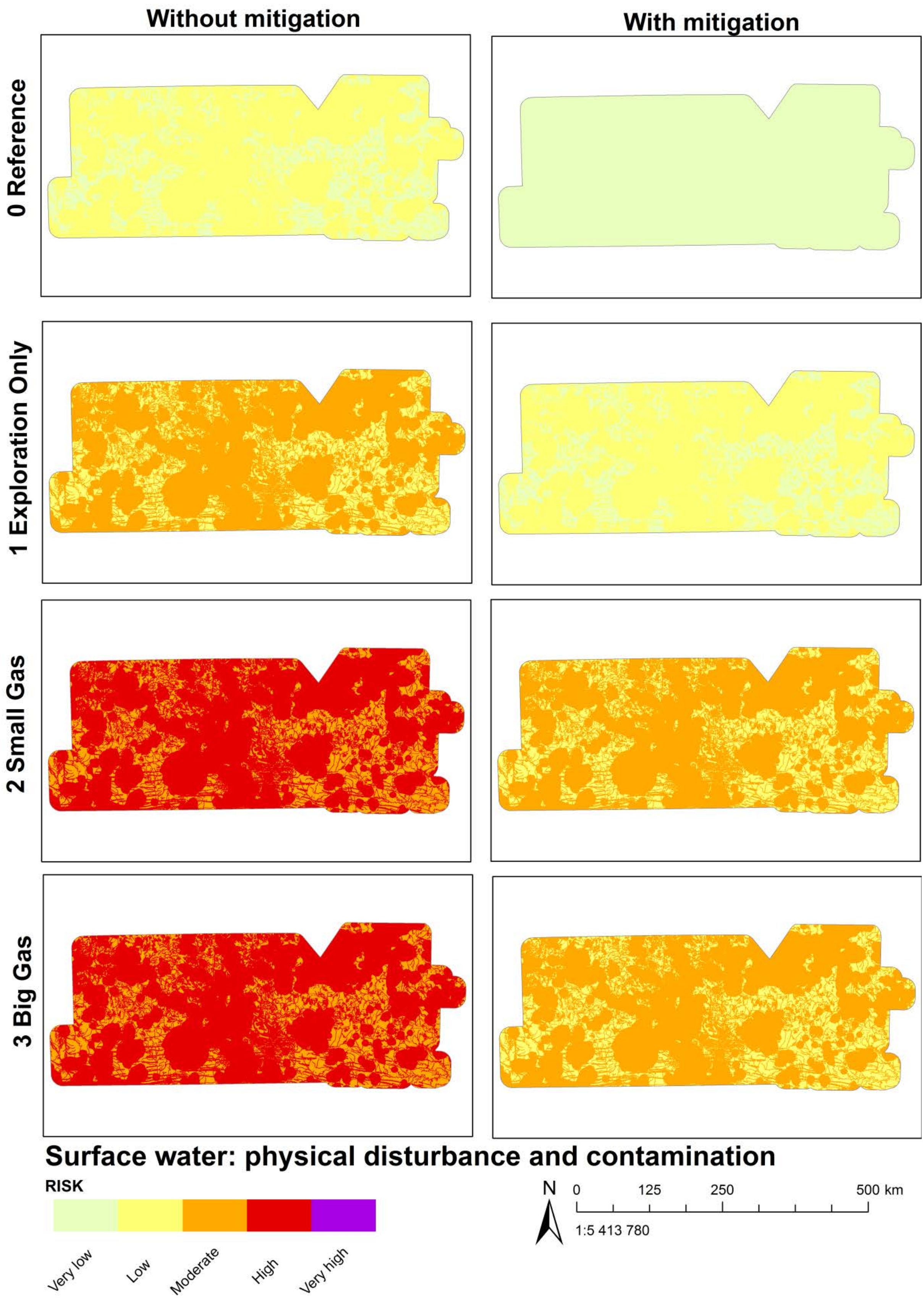

Figure 5.34: Map indicating the risk of physical disturbance to watercourses and contamination of surface water resources through flowback discharge and contact with contaminated groundwater across four SGD scenarios, with- and without mitigation.

Table 5.8b: Surface water risk assessment of indirect impacts.

Note that assessments "with mitigation" in all cases included the assumption that SGD occurs outside of high sensitivity areas shown in Figure 5.28.

Indirect impact	Scenario	Location	*Without mitigation*			*With mitigation*		
			Consequence	**Likelihood**	**Risk**	**Consequence**	**Likelihood**	**Risk**
Effects of increased water demand as a result of population growth	Reference Case	Watercourses including reservoirs in and outside of the study area	Slight	Likely	Low	Mitigation would need to consider proposed approaches at a strategic and then detailed impact assessment level. The risks associated with this impact are not therefore assessed in this study "with mitigation"		
	Exploration Only		Slight	Likely	Low			
	Small Gas		Moderate	Very likely	Moderate			
	Big Gas		Moderate	Very likely	Moderate			
Effects of increased sewage treatment requirements	Reference Case	Watercourses including reservoirs affected by WWTW effluent from new and existing settlements affected by population growth	Slight	Likely	Low	Given the complexity of mitigation at a strategic level and the number of unknowns at this stage, the risks associated with this impact have not been assessed in this study "with mitigation".		
	Exploration Only		Slight	Likely	Low			
	Small Gas		Moderate	Very likely	Moderate			
	Big Gas		Moderate	Very likely	Moderate			

5.7 Best practice and mitigation guidelines

5.7.1 Overview of Best Practice Guidelines

Stephens (2015) presents an insightful analysis of the US EPA Pavillion groundwater investigation that sought to investigate the impacts of fracking on groundwater in the Pavillion natural gas field. The Pavilion investigations attracted considerable criticism from all quarters, exposing in particular deficiencies in its field methods, transparency of its reporting, clarity of its communication and peer review process. This learning experience unequivocally identified the collection of baseline groundwater quality data prior to initiating fracking as an effective way to evaluate potential impacts. Esterhuyse et al. (2014) provide a detailed assessment of monitoring requirements and protocols to ensure responsible SGD by means of fracking.

Applying relevant local and international best practice guidelines (BPG's) is an important mitigation measure as outlined in Section 5.6. The then DWAF drafted extensive BPGs for mining, including Hierarchy guidelines, General guidelines and Activity guidelines. Although developed for mining, many of their principles are also relevant to oil and gas exploration and extraction, as outlined below.

The following hierarchy guidelines are relevant to fracking:

- BPG H1 (Integrated mine water management) (DWAF, 2008a),
- BPG H2 (Pollution prevention and minimisation of impacts) (DWAF, 2007a),
- BPG H3 (Water reuse and reclamation) (DWAF, 2006a) and
- BPG H4 (Water treatment) (DWAF, 2007b).

General guidelines that are relevant include:

- BPG G1 (Storm water management) (DWAF, 2006b),
- BPG G2 (Water and salt balances) (DWAF, 2006c),
- BPG G3 (Water monitoring systems) (DWAF, 2006d) and
- BPG G4 (Impact prediction) (DWAF, 2008b).

Activity guidelines that are relevant include:

- BPG A2 (Water management for mine residue deposits) (DWAF, 2007c) and
- BPG A4 (Pollution control dams) (DWAF, 2007d).

Various candidate technologies and practices for reducing impacts on water resources can be implemented and are listed in Table 5.9 as examples of practices that could be included when formulating policies around SGD mitigation.

Table 5.9: Candidate technologies and practices to reduce the impacts of SGD on water resources (data from Mauter et al., 2013). Scale of benefit: scale(s) at which environmental benefits of technology are most applicable; Adoption: prevalence of technology (legally required in some places, widely used and/or emerging); Type: T = discrete technologies, M = shifts in management decisions, R = feasible regulatory intervention points.

Measure	Scale of implementation	Scale of benefits	Degree of adoption	Potential environmental benefits	Type
Laying impermeable liner over wellpad site	Stimulation well	Local	Wide	Reduces risk of soil and surface water contamination	TR
Laying re-usable mats over wellpad site and planned access routes, rather than laying gravel		Local Regional	Emerging	Reduces risk of soil and surface water contamination; speeds reclamation process once well is put on production; reduces risk of erosion damage	TR
Installing containment walls or dikes around all equipment used to store hydrocarbons		Local	Wide Legal	Contains potential spills and fires	TR
Setting surface casing at greater depths (API recommendation is 100 foot below the deepest aquifer)		Local	Wide Legal	Provides additional separation of groundwater from drilling activities	MR
Cementing intermediate casing, if present, to surface		Local	Wide Legal	Provides additional layer of pipe and cement between borehole and the aquifers it passes through *(may not be applicable for all wells)*	MR
Extending cementing on production casing further above the fracturing zone – to the surface if practicable (API recommends 500 foot above the highest formation to be fractured)		Local	Wide Legal	Reduces risk of interzone migration of sub-surface hydrocarbons	MR

Measure	Scale of implementation	Scale of benefits	Degree of adoption	Potential environmental benefits	Type
Collection and analysis of surface and sub-surface data, used to inform planning and real-time management of fracking		Local Regional	Emerging	Optimises fracturing programme, reducing water use and waste water associated with non-productive fractures, thereby also decreasing truck trips required per well; reduces risk of fracturing beyond desired zone; enables detection of wellbore instability induced by high pressures, reducing risk of rupture and leakage of fluids	TMR
Transitioning to more environmentally benign fracking fluids		Local Regional	Emerging Wide	Reduces chemical hazard of waste water **May conflict with water re-use strategies*	TR
Including non-radioactive tracers in injected proppant		Local	Emerging	Facilitates monitoring of fracture locations and fluid flow within them, detection of communication with aquifers	TR
Conducting small-scale test run (mini-frack) before commencing full fracking job		Local	Emerging Wide	Reduces risk of casing and cement failure under fracturing pressures	TMR
Installing remote-controlled downhole system of permanent monitors, packers and sealing elements, used to optimise flow rates of hydrocarbons and waste water (intelligent completion)		Global	Emerging	Allows dynamic adjustment of in-hole equipment throughout the life of the well, increasing production trade-off for drilling operation	TM
Air and water quality sampling throughout the life of the well (including baseline), used to inform operations.		Local Regional	Wide Legal	Enables immediate detection and mitigation of spills and leaks	TMR

Measure	Scale of implementation	Scale of benefits	Degree of adoption	Potential environmental benefits	Type
Waste water recycling and re-use, through blending and/or treatment	Stimulation well & Surrounding area	Local Regional	Emerging Wide	Reduces volumes of freshwater input and waste water output of each well (requires coordinated completions scheduled across development area and may require alteration of fracking fluid composition to accommodate higher concentrations of dissolved minerals)	TMR
Reuse of drilling fluids and muds (closed-loop drilling)		Local Regional	Emerging Legal	Reduces solid waste; for 100% recycling, requires coordinated drilling schedule and/or large-volume storage capacity across the development area to make use of fluids	TMR
Using double-ditching (preserving topsoil layering) when burying equipment in undisturbed areas		Local Regional	Emerging Legal	Reduces land use impact by preserving soil integrity, native plant root structure and seedstock, and existing microfauna	MR
Capturing fugitive methane by implementing reduced emission completions (green completions) replacing high-bleed valves, installing vapor-recovery units on tanks, etc.		Local Regional Global	Emerging Wide Legal	Reduces carbon footprint of individual wells and development area; reduces emissions of ozone precursor compounds, such as VOC's and NO_x from wells, flares and equipment	TMR
Implementing an inspection plan on a set schedule for all pipes and equipment		Local Regional	Emerging Wide	Enables immediate detection and mitigation of spills and leaks	MR
Clustering wells around a centralised water supply of sufficient volume	Surrounding area	Local Regional	Emerging	Reduces freshwater transport distances; with planning, reduces flow reduction impact of water sourcing on small- surface waters by allowing small withdrawals over time rather than larger ones at the time of use	M
Centralised pumps and impoundments with pipes, used to frack multiple surrounding sites *(centralised fracturing)*		Local Regional	Emerging	Reduces truck trips needed to move fluids and equipment to individual sites	TM

Measure	Scale of implementation	Scale of benefits	Degree of adoption	Potential environmental benefits	Type
Installing temporary pipes to transport large volumes of water for short-term needs (e.g. fracking)		Local Regional	Wide	Reduces truck trips required for freshwater	TMR
Burying corrosion-resistant lines and pipes for longer-term operations		Local Regional	Emerging Wide Legal	Reduces truck trips where used as an alternative; reduces collective surface impacts of infrastructure within greater development area; may reduce the risk of rupture relative to above-ground lines	TMR
Planning multiple wells per pad		Local Regional Global		Reduces collective land use footprint of operation; reduces trucking distances (equipment centralised); maximises production trade-off for wellpad	MR
Surveying and data collection to choose the least environmentally sensitive site from which the target formation may be effectively accessed		Local Regional	Emerging Legal	Reduces land use conflicts and/or absolute magnitude of ecological impact	TMR

5.7.2 Technologies and practices to mitigate SGD impacts on water resources

- **Water re-use and reclamation**: These practices; also specified in Table 5.8 and BPG H3, would help ensure sustainable use of water if this principle is also applied to fracking. The development of water reuse and reclamation plans for fracking operations is encouraged, as well as using alternative processes (e.g. using carbon dioxide or gels for fracking procedures instead of water), as additional mitigation measures. To minimise the impact of accidents or spillages linked to chemicals and waste water management, provision should be made for extreme flood events of the Karoo environment (Figure 5.12). Constructed fracking fluid and waste water containment tanks should be appropriately lined with materials that will not be susceptible to chemical attack or deterioration, and should make provision for the 1 in 50 year flood event. GN R446 does not allow for any storage of fracking fluids or waste water in open pits. In terms of stormwater management BPG G3 outlines basic principles such as separating clean and dirty water systems and collecting and containing dirty water.

- **Regulatory tools and performance standards**: These approaches allow the industry to internalise externalities. Regulatory tools such as casing/cementing depth regulations (Table 5.8), specified in GN R466 in production wells "…… to a depth of 60 m below the base of the deepest freshwater or at least 100 m above the top of expected petroleum bearing zones, whichever comes first ....…" is an example of a "command and control" regulatory tool. Performance standards by contrast may for example require that concentrations of specified pollutants in streams near drilling sites not exceed a certain level or that a pressure test on casing cement not exceed a given reading. GNR 466 specifies such boundaries for pressure test results. Case-by-case permits requires that operators comply with regulator specifications per activity (on a case-by-case basis), similar to specifying licence conditions for a specific activity. Government may use a hybrid of all these approaches in managing oil and gas to minimise environmental impacts. According to Richardson et al. (2013), command-and-control was the predominant regulatory tool and it is possible that this would also be the case in South Africa.

- **Establishing baseline conditions and monitoring:** Water resources monitoring (see Section 5.8 and Digital Addendum 5F) is another important contributory measure to assist in the protection of water resources. For groundwater monitoring, a baseline system of deep and shallow monitoring wells and piezometers should be established in areas expecting significant development, before that development begins. Surface water resources similarly need baseline monitoring (discussed in more detail in the monitoring section). The DWA BPG G3 monitoring guideline specifies the development of environmental and water management plans based on impact and incident monitoring as well as the generation of baseline data before project implementation. Baseline data must as a minimum be relevant to the operation under consideration – if fracking is required, then detailed baseline monitoring of surface and shallow to deep aquifers is required, addressing the full suite of parameters outlined in Section 5.8 and identifying the features outlined in Table 5.10 and Section 5.7 from which activity-based setbacks would be required. The hydraulic properties of the geological formation in the vicinity of initial exploration wells in any new fracking block should be established before additional fracking wells are created as this provides information as to likely geological conditions as well as groundwater quality and distribution. The use of tracers to assist in establishing the direction of groundwater movement from wells may be included in geohydrological assessments, to assist with the optimum siting of groundwater and surface water monitoring points, noting however the limitations of tracer tests, particularly at depth, where the rate of groundwater movement may be very slow. Monitoring should occur before, during and after SGD, and monitoring during well suspension and after well decommissioning is especially important to detect any failure in well construction with possible resultant leakages after fracking occurred. **It is important to note, however, that post-closure monitoring in itself does not constitute mitigation for groundwater contamination**; it is a tool to detect groundwater contamination and initiate rehabilitation measures and should be linked to a management plan to address detected pollution events. Specific recommendations related to monitoring are discussed in the section on monitoring framework and requirements.

> ***Setbacks as a precautionary tool***
>
> It is difficult to mitigate for the failure of well integrity after well decommissioning. Although GN R466 specifies that a well must have a decommissioning plan that must consider amongst other factors the current condition and design of the well, the difficulties in injecting cement into the annulus and future monitoring of the integrity of the plug before being decommissioned, there are no guarantees that over time (decades and longer) decommissioned wells would not leak. This is a serious concern to the authors and is also highlighted as a concern internationally (Davies et al., 2014; ANU, 2012; Bishop, 2011; DEP, 2009).
>
> This aspect underlines the importance of the precautionary approach and the application of stringent setback distances from valuable water resources and possible pathways.

5.7.3 Potential setbacks

The most general way to protect vulnerable water resources is by using command-and-control regulatory tools in the form of setbacks i.e. “no-go” areas. The aim of setbacks would be to establish sufficient distance between sources of impact associated with fracking and its ancillary activities, to prevent contamination or other effects on high sensitivity water resources or pathways to such resources. At the same time, the use of setbacks would also allow for the protection of fracking-associated activities, development and infrastructure, by ensuring that these are sufficiently distanced from areas where aspects of the water resource (e.g. floods) might impact on their safety or operation.

In recommending setbacks, the following considerations have been made, and provide the rationale for setback recommendations outlined in Table 5.10.

- **Identifying relevant geological structures:** The sub-surface should be mapped prior to fracking operations for the presence of faults, shear zones, fold axis, dolerite dykes and sills, kimberlites and diatremes and the measurement of their properties as well as other relevant structures of concern. Artesian features and hot springs must also be mapped, noting that geological structures plotted on the 1:1 000 000 scale data from the Council for Geoscience (CGS) does not show all possible geological features that are present, and need to be identified on a more localised scale. During the EIA, 1:50 000 geological structure data should be used to determine setback distances for these features. Seismic data may also be used to determine sensitive geological structures, and the CGS has deployed six new seismic stations in the proposed Shell SGD areas, of which three, near Graaff- Reinet, are already operational (Saunders, pers. comm. 2016). The setback distance should be based on a reasonable risk analysis of fracking increasing the pressures within the fault/fracture. The properties of the target shale gas formation and upper bounding formations should be verified, post-fracking, to assess how the hydrogeology will change.

- **Considering Karoo dolerite dykes:** The following aspects are important in the determination of setbacks from Karoo dolerite dykes, with buffer widths being calculated as per the method outlined in Digital Addendum 5D, as recommended by Woodford (pers. comm., 2012):

    - Dolerite dykes typically range in width from 3 to 15 m and are seldom wider than 20 m. Dykes with widths <3 m usually represent short, shallow-seated intrusions, whilst the more extensive, regional dykes are typically significantly thicker (i.e. an E-W ‘shear’ dyke north of Victoria West is ~65 m wide, the width of the ‘Gap’ dykes in the eastern Karoo Basin often exceed 100 m) and can extend over lengths in excess of 300 km. Dolerite dykes represent groundwater provisioning targets in the Karoo and also represent areas of possible recharge. They are thus also potential pathways between contaminants occurring in both surface and groundwater activities during fracking and associated activities.

    - The regional E-W orientated dykes of the western and central Karoo Basin, as well as the associated N110º, N150º and N70º fracture systems, display a pattern in accordance with a typical right lateral shear zone. During emplacement of these dykes the maximum compressive stress was vertical, and therefore all fracture orientations could potentially be ‘open’.

    - Dykes are often not mapped as continuous features as they are often ‘masked’ by overburden, exhibit small scale offsets, etc. Each dyke must be reviewed and if necessary all co-linear dyke segments must be manually 'joined' to form a single contiguous dyke feature (i.e. a single poly-line) to estimate the 'actual' length of the dyke (or dyke 'corridor' in the case an en-échelon dyke system).

- **Identifying thermal springs:** Groundwater temperatures may be used as an indicator of the depth of groundwater circulation and therefore the relative scale of flow within the aquifer system. In reality, the depth may be greater because cooling typically takes places during upward flow along fractures to the surface. Jones (1992) found that the geothermal gradients in South Africa vary from as low as 8°C/km to as much as 40°C/km, whilst a value of 30°C/km is more typical for Karoo rocks. Woodford (2012) suggested a method for calculating thermal spring setbacks (see Digital Addendum 5D), and this is used in deriving the setback recommendations outlined in Table 5.10.

- **Identifying aquatic resources**: Proposed sites for shale gas exploration and/or appraisal wells should be subjected to in-depth EIA studies, that allow for ground-truthing of the proposed fracking blocks and their surrounds, with particular attention paid to the need for and siting of exploration boreholes, as well as the identification and characterisation of watercourses, springs, isolated pans and other wetland types, and groundwater-linked artificial systems such as windpump-operated dams and reservoirs. A full inventory of such systems should be required, with the study area extending at least one kilometre in all directions outside of and including the proposed fracking block. High value water resource landscapes and waters (such as surface water and groundwater source zones, groundwater recharge areas and zones identified for artificial recharge) should be protected for future use and to ensure sustainability of water resource use. The following issues have a bearing on the setbacks outlined in Table 5.10 for these aspects, namely:

    - Current water supply wellfields are regulated in GN R466 to have a setback of 5 km around these areas. In this assessment, it is advocated that artificial recharge (AR) sites should also be protected with a similar setback, as these sites are equivalent to wellfields and can possibly in future be used as abstraction wellfields (in the absence of excess surface water for storage) or as AR areas (DWA, 2009). Protecting AR areas with horizontal setbacks in addition to the vertical protection zones based on the fact that shale gas horizons are thousands of metres away from sensitive shallow water source features, as well as the protection of geological features with setbacks within the AR areas, is an example of the application of the precautionary principle.

    - With regard to the establishment of setback lines from surface water resources, it is noted first that horizontal distance from a well may be irrelevant as a mechanism to ensure protection from groundwater contamination or accidental drainage of wetlands as a result of groundwater drawdown through puncturing of perched layers. Actual setback lines would need to be determined on a site by site basis, with reference to geohydrological modelling. However, some setback requirements should be regarded as mandatory in all cases, and would need to be inherent in any application, regardless of the outcomes of geohydrological assessment. These include:

        - floodplain setbacks based on reducing the risk of flooding of fracking infrastructure including waste storage;
        - reducing the risk of drawdown of, or the creation of new surface/groundwater pathways between watercourses, pans or other water resources, by using setbacks

that take cognisance of the likely extension of sub-surface fracturing beyond wellbores – it is mentioned in Burns et al. (2016) that fractures may extend outwards for distances of up to 300 m from the wellbore;

* consideration of downstream storage devices such as dams and their role in possible broader contamination pathways (e.g. through the export of water);
* consideration of the need to maintain or improve watercourse resilience against adjacent impacts likely to impact on natural runoff, sediment transport and water quality patterns; and
* consideration of known/visible zones of surface/groundwater interactions in the form of areas of recharge or daylighting of springs (hot or cold) or seeps. Cold and hot springs with associated seismic activity would need a greater setback than normal, as drilling and well stimulation activities may trigger earth tremors in these areas. Springs with known seismic activity include Middelburg and Leeu-Gamka (Saunders, pers. comm. 2016; Fynn et al., 2016).

Table 5.10 outlines multiple setbacks that could be applied at an EIA-level investigation to reduce risk associated with proposed SGD activities, and includes reference to existing South African regulations that currently specify setbacks. It should be noted that these setbacks are deliberately conservative, taking cognisance of the low confidence associated with identification of impacts associated with many aspects of the anticipated activities. For example, there are uncertainties as to actual aquifer extent; mapping of many geological features and important geohydrological attributes has been carried out at a very coarse scale (1: 1 000 000 in some cases); mapping of watercourse and isolated wetland features is not necessarily of a high degree of accuracy and the floodlines of most watercourses in the study area have not been determined. Given that the consequences of contamination or other impacts to surface and groundwater resources might be considerable and possibly permanent and irreversible (Section 5.6), it is appropriate to err on the side of caution in the formulation of spatial depictions of setback and exclusion areas.

The actual spatial implications of the recommendations outlined in Table 5.10 for the present study area are presented in Figure 5.25 to 5.28, while Digital Addendum 5E presents a breakdown of these data for individual components specified in Table 5.10. The most useful application of these figures is in their indication of relatively high confidence that the areas NOT outlined as setback areas could be targeted for SGD activities (i.e. areas of medium sensitivity), with a low risk of impact to surface or groundwater resources. By contrast, not all areas included in these setback zones need be regarded as 'no-go' areas. The mapped zones in some cases indicate setbacks within which more detailed information would be required to determine likely impacts and appropriate levels of mitigation. For example, watercourses have been buffered by a setback of 500 m for "ancillary activities" (that is, activities associated with SGD excluding actual fracking). This setback is simply a trigger for further investigations in terms of both the NEMA and the NWA, to determine an appropriate setback for the actual site in question. In other cases, the setbacks are conservative in the absence of detailed mapping information – dolerite dyke buffers, for example, have been calculated for curvilinear rather than straight dykes across the study area, given that the setback calculations outlined in Digital Addendum 5D allow for these to be wider than for alternative straight dykes. The figures outlined below need to be interpreted from the perspective of highlighting areas where SGD might proceed with low risk of incurring <u>direct</u> impacts to water resources, rather than as implying that all areas mapped are considered absolute 'no-go' zones from the outset. Detailed investigations would be required to elucidate whether additional areas may be exploited without risk to water resources, and by implication to their associated dependent ecosystems and human communities.

Table 5.10: Recommended setback distances which were used to develop the sensitivity map. Specified separately for (1) stimulation well activities and (2) ancillary activities including stratigraphic wells, horizontal wells and the establishment of roads, wellpads, waste stores and other activities.

Concern	Sensitivity / Setback aspect		Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
Stimulation well (with associated fracking)	Water source features	Municipal water well fields, artificial recharge areas, areas of shallow groundwater (<10m) or groundwater source zones.	Not within 5 km, measured horizontally, from the surface location of an existing municipal water wellfield and identified future wellfields and sources and directional drilling may not be within 2.5 km of municipal wellfields[1]	Agree with GR R466 setback distance. Apply this setback distance for artificial recharge areas and groundwater source zones as well. Where town wellfield is not known, identify town water source, if groundwater or a combination of groundwater and surface water, then use built-up area of town and buffer by 5 km, in accordance with precautionary principle. Exclusion area: Exclude areas where the wet season water table lies at or closer to 10 m from the surface.	Five (5) km between a stimulation well and 2.5 km distance between directional drilling and municipal water wellfields are sufficient based on known hydraulic properties of shallow Karoo aquifers. Where information regarding the presence of municipal water wellfields is limited but the settlement is shown in ‘All Towns’ data as having groundwater or combined groundwater and surface water dependence, there is also a precautionary need to buffer these areas from SGD activities. These shallow groundwater areas are considered of high sensitivity to SGD activities.
		Water supply boreholes or water storage dams	Not within 500 m, measured horizontally, from the surface location of an existing water borehole and directional drilling may not be within 500 m of the borehole[1]	No closer than 1 000 m from any domestic, stock watering or irrigation supply borehole or downslope storage dam, and directional drilling may not be within 500 m of the borehole.	The setback distance recommended in GN R466 is not stringent enough for fractured rock, which represent preferential pathways for contamination migration in the Karoo. Water scarcity in the Karoo and the high dependence on groundwater resources also necessitates a more stringent setback distance.
		Watercourses	Not within 500 m, measured horizontally, from the edge of a riparian area or within the 1:100 year floodline of a watercourse. No structure or facility within 1:100 floodline or within a horizontal distance of 100 m from a watercourse, estuary, borehole or well[2]	No closer than 500 m from the 1:100 year floodline or outer edge of the riparian zone (whichever is the greater) of any watercourse or from the temporary or other outer edges of any other wetland type	This value is based on a horizontal safety factor of 200 m, over and above the estimated 300 m to which horizontal fractures are likely to extend from fracking wells (Burns et al., 2016). This setback is conservative, and driven by the high risks associated with these activities.

Concern	Sensitivity / Setback aspect		Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
		Pans (isolated wetlands)	None	No closer than 300 m from the delineated temporary edge of any perched, isolated seasonal pan (i.e. not on a drainage line)	Such pans are not expected to be in direct contact with groundwater nor do they form part of significant conveyance corridors for sediment and contaminants. The 300 m setback derives from the 300 m to which horizontal fractures are likely to extend from fracking wells (Burns et al., 2016).
		Cold springs	None	No closer than 1 000 m from the upslope delineated outer edge of any cold spring, and no closer than 300 m downslope Setback distance = 5 000 m from springs within region of known seismic activity. Example: Middelburg cold springs area.	Springs represent zones where there is probable vertical/horizontal connectivity between surface and groundwater resources. Springs with associated seismic activity may be associated with active geological structures where drilling and well stimulation may trigger earthquakes, and would need a larger setback. The downslope setback derives from the 300 m to which horizontal fractures are likely to extend from fracking wells (Burns et al., 2016).

Concern	Sensitivity / Setback aspect		Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
		Thermal springs (water temperature >25º C), artesian boreholes, artesian aquifer zones and artesian SOEKOR wells.	None	Calculate buffer zone (Woodford, 2012) $$EZ_{SP} = \frac{T_{GW} - T_{MA}}{G_T} \times \arctan(\phi)$$ Where: EZ_{SP} - Radius of the circular Buffer Zone at the surface. T_{GW} - Temperature (ºC) of thermal spring. T_{MA} - Mean annual air (ºC) (possibly use Schulze's climatological dataset)/Possibly use average temperature of the shallow (5-10 m below water table) groundwater. G_T - Geothermal gradient (ºC/m) for Karoo Basin (assumed 0.03ºC/m) Ø - Angle (Digital Addendum 5D), currently assumed to be 30º, to take account of potential dip/width of fracture system (tortuous preferential flow path) from source to surface. Investigate structures linked to springs in detail during EIA to delineate any previously unidentified flowpaths and buffer such zones. Setback distance = 1 000 m from centre point where no temperatures available. Setback distance = 5 000 m from thermal springs within region with known seismic activity. Example: Thermal springs in the Leeu-Gamka seismic zone.	Thermal springs specifically are associated closely with deeper geological structures (Kent, 1969), usually with faults and folds (Olivier et al., 2011) as well as dykes. High water temperatures as well as thermogenic methane associated with some thermal springs indicates definite deep connections (Talma and Esterhuyse, 2013). Thermal springs are likely to have source recharge areas many kilometres from the spring discharge area and these must be delineated during the EIA prior to setting site-specific setback distances. Springs with associated seismic activity may be associated with active geological structures where drilling and well stimulation may trigger earthquakes, and would need a larger setback than normal.

Concern	Sensitivity / Setback aspect		Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
	Geological features (based on 1:1,000,000 scale CGS data)	Dykes	None	Join co-linear dyke segments to estimate the 'actual' length of the dyke. Calculate Buffer setback zone (Assume mapped dyke is linear in outcrop, likely dip variation thus between 85º and 89º). $EZ_{85^\circ} = \left(0.186 \times D_L^{0.65}\right) + \frac{D_W}{2}$ (Eq. 1) $EZ_{89^\circ} = \left(0.046 \times D_L^{0.65}\right) + \frac{D_W}{2}$ (Eq. 2) Where *EZ:* width of Buffer (metres) D_L: Length of Dyke (metres) D_W: Dyke Width Dyke width can be measured in the field, estimated from high-resolution aerial photography or aeromagnetic imagery, or by using of the following equation: $D_W = 0.1 \times D_L^{0.54}$ (Eq. 3) If the estimated width of the calculated dyke buffer *EZ* is <250 m, set buffer to 250 m. Note that in practice mapped dykes must be differentiated as separate polygons and not intersecting lines, in order to calculate length.	The thicker the dyke, the wider the buffer zone must be. Dolerite dykes must be buffered because they represent one of the main targets for water supply borehole siting in the Karoo and also represent areas of possible groundwater recharge and preferential flow.

Concern	Sensitivity / Setback aspect		Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
		Kimberlites and diatremes	None	500 m radius from centre point of structure	Kimberlites have complex associated emplacement models (Field and Scott-Smith, 1999; Skinner, 2009) and the surface and underground morphology of these structures may be quite large and varied (Field and Scott-Smith, 1999; Woodford and Chevallier, 2002; Pacome, 2010), with surface outcrop morphology varying from 1 ha to >15 ha (Skinner, 2009). A 500 m buffer zone is recommended based on expert input (Esterhuyse et al., 2014).
		Faults, shear zones and fold axis	None	1 000 m from centre line of structure	250 m buffer was suggested by Rosewarne et al. (2013); however one expert stated that unless these features are mapped in detail, a buffer of 250 m is too narrow. Fold axes must be treated separately as their fold axis limb angles should be considered which may push the distance to several kilometres. A buffer of 1 000 m is thus recommended (Esterhuyse et al., 2014).
		Dolerite sills	None	250 m from rim of surface outcrops	Morphology of sill surface outcrops may not be representative of underground morphology (Rosewarne et al., 2013). The researcher suggested the applying the precautionary principle with a buffer zone of 250 m from the rim of these structures. One expert stated that a differentiated approach should be used here, since transgressing sills are complex and a dislodged contact may reach all along the contact zones, which might stretch for kilometres. Bedding plane sills may offer a high security to percolating fluids/gasses from the shale gas source. A buffer of 250 m is used here in lieu of more detailed data and to adhere to the precautionary principle (Esterhuyse et al., 2014)

Concern	Sensitivity / Setback aspect		Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
		Undifferentiated geophysical anomalies	None	1 000 m from centre line of feature	Depending on the structure geometry, SGD should be limited near these features. Unless detailed geophysical investigations have been conducted, the buffer should be 1 000 m, based on expert input (Esterhuyse et al., 2014).
Exploration, production and ancillary SGD activities (including wellpad establishment, drilling, waste water management, cleared vegetation, access roads, infrastructure, sanitation)	Artesian boreholes, artesian aquifer zones and artesian SOEKOR wells (KL 1/65, SA 1/66, VR 1/66, CR 1/65)		None	Calculate setback distance based on thermal spring methodology. **Setback distance = 1 000 m from centre point where no temperatures are available.** Also recommend that these features be investigated in detail during EIA to delineate any previously unidentified flowpaths and buffer such zones.	Artesian aquifer zones represent areas of possible deep/shallow groundwater connectivity.
	Deep recharge zones		None	Protect the source area and investigate these zones in detail during the EIA to delineate any flowpaths to shallow aquifers and then buffer accordingly.	Van Wyk (2010) postulates an 'L-shaped' recharge flow path from vertical source areas, laterally into aquifers. Such source areas are likely to be topographic highs such as the Great Escarpment and large dolerite/sandstone capped ridges/escarpments

Concern	Sensitivity / Setback aspect	Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
	Water resources (water courses including mapped dry river courses, wetlands, pans, shallow aquifers, cold and thermal springs) and water supply infrastructure (water supply boreholes, wellfields, water storage dams)	No mining, prospecting or any other operation under or within the 1:50 year floodline or within 100 m from any watercourse or estuary, whichever is the greatest[2]. No residue or substance which may cause pollution in underground workings, pit or excavation[2]. No sanitary convenience, fuel depot, reservoir or other depot for any substance which may cause pollution within the 1:50 year floodline or within 100 m from any watercourse or estuary, whichever is the greatest[2]. No structure on water-logged ground or on ground likely to become waterlogged[2]. No water use in terms of Section 21 c and 21 i of the NWA allowed within a 500m radius from the boundary of a wetland[3]. No alteration the bed, banks, course or characteristics of a watercourse within the 1:100 floodline or within the riparian habitat, whichever is the greatest[3].	Exclude areas where the wet season groundwater lies at 10 m or closer to the surface. No closer than 1 000 m from water supply sources infrastructure (domestic, stock watering or irrigation supply borehole or downslope storage dam or water supply wellfields). Where town wellfield is not known, identify town water source, if groundwater or a combination of groundwater and surface water, then use built-up area of town and buffer by 1 km, in accordance with precautionary principle. No closer than 500 m from any thermal spring or cold spring No closer than 500 m from any identified watercourse or other wetland type <u>without a detailed ecological, hydrological and geohydrological investigation.</u> Setback distance = 5 000 m from cold or hot springs within region of known seismic activity. Example: Middelburg cold springs area. Leeu-Gamka hot spring area. Springs with associated seismic activity may be associated with active geological structures where drilling may trigger earthquakes, and would need a larger setback than normal. As a general guideline, structures and infrastructure should be located at least 100 m from the delineated edge of any watercourse or other wetland and such that they do not impact on their condition, characteristics or function.	Shallow groundwater resources are at higher risk of contamination from exploration, appraisal and fracking activities. Ancillary activities including storage and transport of fracking fluids, chemicals or waste water are all considered potential contamination activities in terms of spills and leaks, representing a risk to water resources. Areas of cleared vegetation for seismic surveys or wellpads, roads, storage areas for equipment, water, chemicals and waste should not be closer than 500 m from thermal springs and cold springs in order to protect them from impacts related to these ancillary activities. This is a conservative width but takes cognisance of the possible high concentration of impacts/disturbance associated with the activity and risks associated with surface spills of contaminated flowback water or stored waste.

Concern	Sensitivity / Setback aspect	Setback distances in existing regulations GN R466[1] / GN 704[2] / GN 1199[3]	Potential setback distances and exclusion areas	Rationale
	Artificial recharge areas (current and future)	None	5 km around these areas, based on the setback distance in regulations GN R466 for water supply wellfields. Should such areas be managed in terms of inducing maximum drawdowns, then site-specific studies must be carried out to determine the required setback (pers. comm., R. Murray, 2016)	Artificial recharge zones are important to protect for future storage of drinking water and would become more important in water scarce South Africa. It is a more effective water storage method than surface water dams (less evaporation and no sedimentation).
	Geological features	None	No fracking chemicals storage, waste or waste water management infrastructure, fuel depots or sanitation infrastructure within 250 m of geological features listed in this table without a detailed geohydrological investigation.	Geological features may represent areas of possible groundwater recharge and preferential flow, thus potential groundwater pollution sources should not be established near these features. GN R466 makes provision for waste and fluids management, however apply precautionary principle in cases where detailed geohydrological investigations have not been performed for these features and use setback of 250 m.
	Groundwater source zones	None	Not within 5 km of groundwater source zones, based on setback distance for wellfields in GN R466. Source zones in process of being identified in WRC project (pers. comm., A. Maherry, 2016).	Source zones supply the most important aquifers in South Africa.

5.8 Monitoring framework and requirements

Monitoring of water resources is important for minimising, controlling and mitigating against the effects of SGD. Monitoring is key to assessing the condition of surface water ecosystems, which react to changes in flow volume, impacts of land use, and climate. Furthermore, some SGD-generated spatial and temporal changes in surface water ecosystems can be detected only with long-term monitoring. In addition, a comprehensive understanding of groundwater conditions is required prior to the commencement of exploration to ensure proper interpretation of changes in groundwater over time. It is therefore imperative that detailed monitoring plans are developed for the different phases of SGD. Monitoring data would also be used for calibration and verification of prediction and assessment models, for evaluating and auditing the success of management plans, and for assessing the extent of compliance with prescribed standards and regulations.

Monitoring must be linked to a management plan to ensure that water resources are protected and that action is taken when certain set thresholds are exceeded. Ideally, the monitoring plan should address the following:

- design of the initial monitoring programme;
- methods of sampling, collecting and capturing the data;
- methods for analysing the data;
- format for reporting the findings to the relevant authorities;
- mechanisms for auditing, and for recommending and implementing changes to the monitoring programme.

There is little point in monitoring if it cannot lead to changes in SGD practices, so all licences granted to the developers would need to take principles of adaptive management into account. In short, a mechanism would be needed to enforce modifications of SGD activities based on results of the monitoring programme.

Furthermore, it would be difficult, if not impossible, to identify the effects of SGD on surface and groundwater systems without baseline monitoring (Government Accountability Office (GAO), 2012a; 2012b). Long-term data would therefore need to be collected, preferably over at least five years, to identify trends in the biophysical conditions and functioning of these systems in the absence of SGD. Hildenbrand et al. (2016) indicate that groundwater contamination pathways are complex, and that various toxic compounds may be detected in groundwater, seemingly at random times, in areas of high SGD activity. These authors monitored groundwater in an area of increasing SGD over a period of 13 months. They reported ephemeral detections of various organic molecules with minimal co-variation, which suggests that contamination events may be variable and sporadic (as opposed to systematic). Additionally, the accumulation of bromide and various alcohol species indicates that residual changes in groundwater chemistry may persist in regions engaged in SGD. Brantley et al. (2014) note that high-confidence identification of contaminants in water resources as a result of shale gas exploration, appraisal and production activities are often hampered by:

- the lack of information about location and timing of incidents;
- the tendency to not release water quality data related to specific incidents due to liability or confidentiality agreements;

- the sparseness of sample and sensor data for the determinands of interest; the presence of pre-existing pollutants that make it difficult to determine potential impacts from shale-gas activity; and
- the fact that monitoring sensors can malfunction or drift.

Their study showed, too, that in areas where shale gas is developed quickly, baseline data against which future impacts can be assessed are often inadequate. The authors thus highlight the importance of:

- performing baseline water quality monitoring of water resources in areas considered most likely to be targeted, well before exploration drilling commences and according to predefined standardised procedures and flexible reporting templates;
- adequate siting of surface and groundwater monitoring sites so as to allow conclusive assessment of data and identification of possible sources of contamination.

In terms of who must perform the monitoring, the following aspects are important to note:

- Oil and gas companies, government or its appointees, and perhaps independent monitoring institutions, should be involved in monitoring. Monitoring of their operations by oil and gas companies should be required as part of the licensing agreement. Strict reporting requirements, to government and/or other independent institutions, should be in place and results should be independently verified. Government should play an oversight role, which might include verification sampling. It may be necessary to establish an independent laboratory for monitoring aspects such as natural isotopes, constituents of fracking fluids, and uncommon organic substances emanating from fracked wells and local groundwater.

- Government needs to acknowledge the regional and cumulative scale of SGD impacts, and implications for monitoring. Government must align legislation with regard to monitoring, as well as mandates, roles and responsibilities between relevant government departments. If this is not achieved, it will be necessary to institute an independent central entity to perform monitoring functions.

- It is crucial that the monitoring entity be independent, and be perceived as being independent, of the mining companies.

- Monitoring must be carried out in such a manner that the results will have legal standing

Esterhuyse et al. (2014) discuss monitoring of surface water and groundwater in detail, differentiating between monitoring requirements during the pre-development, exploration, development (during extraction) and post-development (after extraction) periods (see Digital Addenda 5F(i) - surface water and 5F(ii) – groundwater). The monitoring frameworks for groundwater and surface water bodies are summarised below.

5.8.1 Monitoring frameworks

Groundwater

In order to perform appropriate baseline monitoring, an understanding of the aquifer systems in an area, as well as migration pathways for contaminants, is necessary. Baseline groundwater quality and quantity also need to be quantified. With regard to water chemistry, the concentrations of constituents naturally found in the water must be known, and monitored, for both shallow and deep aquifers, as well as in additives in fracking fluids. GN R466 requires that SGD companies report their fracking water additives and some of these should be monitored as part of an early warning monitoring system for picking up contamination incidents. The list of constituents to be measured before initiation of fracking should be extensive enough that regulators can identify which are suitable for detecting fracking-related changes (Table 5.11).

During exploration and development, operators should be required to monitor the quantity of water used and other technical aspects such as drilling rate, volumes of drilling and fracking fluids and their constituents, and micro-seismicity at exploration and production sites. Regulators would have to ensure that data dissemination from the operators occurs as required by per license conditions. After SGD has ceased in an area, integrity of wells will need to be monitored. All decommissioned wells need to be monitored annually for well integrity going into the future, taking into account that well failure typically occurs over the long-term (>50 years). The detailed monitoring framework describing the "Why?", "What?", "How?", "Where?" and "Who?" in regard to quantity, quality and technical aspects for groundwater as described by Esterhuyse et al. (2014) can be seen in Digital Addendum 5F(ii).

Surface water

The spatial and temporal monitoring design is crucial to the reliability and usability of surface water monitoring data, as well as identifying the current condition of water bodies in the study area. Water quality, water quantity and habitat integrity should all be measured, together with weather data such as daily precipitation and evaporation. Site selection, sampling and interpretation of results should be done by trained, unbiased, independent, experienced professionals that are familiar with the type of water body (rivers, wetlands), geographical area and sampling techniques to be used. Baseline monitoring should cover all four seasons, preferably for a number of years, including at least a wet and a dry year, at representative sites. Frequency of sampling will need to be increased during wet periods. Long-term monitoring is needed for an understanding of hydrologically variable systems, as occur in the study area. Our limited knowledge of the functioning of these systems renders them particularly vulnerable to inadequately managed perturbations.

Techniques for analysing water chemistry of non-perennial systems should be appropriate, reliable and well tested, and carried out at reputable, accredited laboratories. Water quantity data need to be collected at least weekly, although real-time data collected automatically through gauging stations or water-level recorders is preferable. Baseline water quality data need be collected less frequently - perhaps every three months - except after rain, when daily or weekly sampling may be necessary.

For rivers that flow seasonally or perennially, habitat integrity, geomorphology (using the Geomorphology Assessment Index - GAI), fish (using the Fish Response Assessment Index - FRAI) and vegetation (using the Vegetation Response Assessment Index - VEGRAI) (Kleynhans et al., 2007) might be monitored yearly or after floods or drought. Macro-invertebrate indices are not very reliable for dryland rivers. They should initially be monitored every six to eight weeks *while the water is flowing* but an assessment will need to be made as to their usefulness for monitoring purposes. Current invertebrate indices such as SASS should *not* be used for non-flowing systems. Wetlands, and rivers that have been reduced to standing pools, should be monitored using one or more of a variety of existing methods for assessing *wetlands* (see Ollis et al., 2014). If the Rapid Habitat Assessment

Method (RHAM) is used for rivers then it needs to be monitored at least monthly and if possible weekly, together with the water quality and quantity measurements. The Why?", "What?", "How?", "Where?" and "Who?" is described in more detail in Digital Addendum 5F(i) for surface water.

5.8.2 Water quality analyses

It is important that, as far as possible, the same techniques are used for analysing ground and surface water quality and that the techniques to be used are well recognised and can be measured to a relevant level of accuracy. For instance, while major ions such as Cl^- and Ca^{2+} usually occur in the parts-per-million range of concentrations (mg/L), nutrients such as the PO_4^{3-} ion normally occur in parts per billion (µg/L), and many metals, metalloids and organic contaminants in parts per trillion (ng/L).

In addition,

- Procedures for collection of all water samples need to be specified in detail.
- Exact constituents to be analysed need to be specified.
- Exact methods, and detection limits, need to be specified for all constituents.
- For many of the less common constituents of fracking and drilling fluids, it is necessary to examine chromatograms to see what classes of compounds are present, and then identify those that appear in substantial quantities, because constituents of these fluids are not always divulged by the drilling company (G.T. Llewellyn, *pers. comm.*).
- Isotopic analysis of natural gas is extremely useful for investigating alleged gas drilling impacts and understanding gas source areas. Both methane and ethane should be examined (G.T. Llewellyn, *pers. comm).*

Table 5.11 summarises the list of recommended monitoring parameters. Broadly speaking, electrical conductivity (EC - equivalent to salinity or saltiness) is the most useful measure of background water quality, and is often helpful in identifying the groundwater source (deep or shallow) of the water being tested. The geochemical signature of the deep groundwater is as yet largely unknown, so as much data as possible is needed from these areas to provide background information. The EC of produced water after fracking will often provide information of the depth and strata from which the water emanated.

Analysis of two water samples obtained from SOEKOR well SA 1/66 (Murray et al., 2015) indicates that Br, Ba, F and Sr may be characteristic indicators of deep groundwater in South Africa. This requires further investigation as the level of ingress and mixing of this water is unknown and the sampling methodology was rudimentary.

The isotopic composition of water is a valuable tracer for evaluating water sources and mixing processes in aquifers (e.g. Baldassare et al., 2014). Mayer et al. (2015), for instance, have demonstrated that a multi-isotope approach ($\delta^{13}C_{CH4}$, $\delta^{2}H_{CH4}$, $\delta^{2}H_{H2O}$, $\delta^{18}O_{H2O}$, $\delta^{13}C_{C2H6}$), in concert with chemical analyses, is capable of identifying potential contamination of shallow aquifers with stray gases or saline fluids from intermediate or production zones, provided that sufficient baseline data have been collected. $\delta^{13}C_{DIC}$, $\delta^{11}B$, ^{14}C and $^{87}Sr/^{86}Sr$ ratios would be valuable for identifying deep groundwater in the Karoo (Miller et al., 2015).

In groundwater, noble gas analyses can assist in distinguishing among different sources of hydrocarbons. Analyses of noble gases (e.g. He, Ne and Ar) and their isotopes in groundwater, when paired with hydrocarbon composition (e.g. methane $\delta^{13}C$, CH_4 and C_2H_6) and inorganic water chemistry (e.g. Cl, Ba), can therefore help differentiate between natural geological migration of hydrocarbon gases and anthropogenic contamination (Darrah et al., 2014) and may also help to determine the mechanisms whereby anthropogenic gas contamination occurs.

Radioactivity (gross alpha radioactivity, gross beta radioactivity) and radioactive isotopes also need to be monitored, particularly given the high level of uranium in parts of the Karoo (Subsection 5.2.2).

Table 5.11 provides an initial list of important parameters for monitoring surface and groundwater likely to be affected by SGD. It is not comprehensive and would need to be adjusted in consultation with baseline monitoring results. Cations and anions should be analysed in both surface and groundwater samples, while organics, radioactivity and isotopes will mainly be analysed in groundwater samples with analysis of these parameters only in very specific surface water samples.

Table 5.11: Important water chemistry constituents to be measured in SGD monitoring programmes. Note: analytes indicated in **bold** (Murray et al., 2015, Miller et al., 2015) have been identified in South African shales; analytes indicated in italics have been identified in produced water from gas shales internationally (Orem et al., 2014).

Field	Major ions	Secondary	Minor or trace	Organics	Isotopes	Radioactivity
pH Temperature Electrical conductivity Dissolved oxygen Oxidation reduction potential	Na Cl Mg Ca HCO_3 SO_4	K **F** **Sr** CO_3 NO_3-N B	Al, Pb, *Cd*, CH_4, *Co*, *Cr*, Cn, Mn, **Br**, Si, Phosphate tot, *As*, S, Se, *B*, ***Ba***, Cu, *Fe*, *Hg*, *Zn*, *Ni*, Mo, Hg, U, *V*, Sb, M-Alk. P-Alk. NO_3+NO_2, ORP, pH, TDS, Total hardness, NH_3 (ammonia nitrogen)	*TOC*, *PAHs*, VOC's, SVOC's, BTEX (Specific organic constituents to be specified for monitoring based on fracking water additives reported by O&G companies)	**Stable:** $\delta^{13}C_{CH4}$, $\delta^{2}H_{CH4}$ in groundwater $\delta^{13}C_{H2O}$, $\delta^{2}H_{H2O}$, $\delta^{18}O_{H2O}$, $\delta^{13}C_{DIC}$, $\delta^{13}C_{C2H6}$, $\delta^{2}H_{C2H6}$, $\delta^{34}S_{SO4}$, $\delta^{11}B$, ^{14}C **Radioactive:** *$^{235\ 238}U$, ^{232}Th, $^{226\ 228}Ra$, ^{222}Rn, ^{40}K, ^{210}Pb, $^{87}Sr/^{86}Sr$ ratio*	Gross alpha radioactivity Gross beta radioactivity

5.8.3 Quality assurance and quality control during water quality sampling

To ensure the collection of good quality data during water resource monitoring, standardised monitoring guidelines, sampling quality assurance and quality control (QA/QC), and laboratory and analytical criteria are necessary.

Sampling

- Field sampling procedures should be robust, reproducible and reliable.
- Taking duplicate samples for analyses at the same laboratory and at a quality control laboratory and employing trip blanks/field blanks is advised.
- The sampling should be undertaken by an accredited institution and accredited and appropriately trained individuals.
- The appointed institution needs to be unbiased and independent and should not be connected to any of the interested parties.
- Sampling and handling methods used need to be clearly documented.
- Copies of the chain of custody (COC) forms must be kept. Sample results must be traceable back through their collection, storage, handling, shipment and analyses; and information on persons handling the sample should be completed on a COC form.
- Data must be analysed and interpreted by individuals experienced in the particular field (e.g. water quality, fish), geographic locality and the type of system (wetland, non-perennial river, groundwater) sampled.

Laboratory and analytical criteria

- It is recommended that the selection of the preferred laboratories be based on quality, detection limits, and number of parameters which can be analysed.
- The quantification limits for all parameters used in assessing water for human consumption must, if available, be based on the SANS (2015a; 2015b) drinking water standards; South African Water Quality Guidelines for Agricultural Use (Livestock watering) are useful guides for suitability of water for livestock to drink. Where no guideline values have been published, international standards should be used to assess the water quality results.

5.8.4 Data management

The efficient management and safe storage of data are essential prerequisites for a successful monitoring programme and proper data management is therefore important. If the DWS does not have the capacity, an independent entity would need to manage, archive and disseminate the information collected during the monitoring programme.

The DWS keeps records of water quality, hydrology, and river health under the Directorate: Resource Quality Services. Surface water data, including streamflow, rainfall, evaporation and reservoirs, are available in the HYDSTRA, an integrated water resources management software database. Fitness-for-use data are housed in the National Microbial Water Quality Monitoring Programme, National Eutrophication Monitoring Programme, National Toxicity Monitoring Programme, Rivers database, Water Management System (WMS), HYDSTRA and GIS. Current records are too few to be used as baseline data for all proposed unconventional oil and gas mining areas.

For groundwater, the DWS keeps a National groundwater archive (NGA). The NGA can be viewed as the most up-to-date data archive on groundwater in South Africa, and options would have to be investigated to determine if this system can be efficiently adapted to manage oil and gas wellsite-specific information. Options would have to be investigated to streamline the WMS and NGA systems.

Important aspects to be kept in mind in connection with monitoring data are:

- A central database for all data should be curated by a reliable, institution and be accessible to all stakeholders, including the public.
- Monitoring records kept by oil and gas companies should also be accessible to all.
- Good record keeping is an essential part of quality assurance. Original datasheets should be kept for as long as possible. It is also vital that the transcription of data from data sheets to electronic format is accurate and validated, and that this is done by a competent person who understands the data and who is capable of data interpretation (DWAF, 2008).
- Data needs to be examined for irregularities immediately after collection and any identified impacts should be communicated to the relevant government department and to the company causing the impact as soon as possible.

Data requirements differ for each of the life cycle phases of SGD and this should be taken into consideration when prescribing monitoring requirements. Adequate data capture of development operations is a crucial part of proper monitoring and management of this activity internationally (Atlantic Council, 2011). Developing a database system similar to Fracfocus (Fracfocus, 2016) and a linked online mapping system such as Fracktracker (Fracktracker Alliance, 2016) would be ideal.

5.9 Gaps in knowledge

The assessment has necessarily identified a number of aspects for which available information is inadequate for scientifically sound decision-making purposes. This is as much a function of the complexity of the deep sub-surface hydro-environment such as is currently being revealed in a very few localities, as it is by the erratic and variable nature of event-driven surface flow. Factoring in the uncertainties associated with climate change adds another level of intricacy to an already complex environment. The following list identifies, in no specific order of significance, those aspects that are considered limiting factors in this assessment.

- The paucity of reliable information regarding groundwater use (both for municipal/town water supply and agricultural purposes) in the study area is identified as a critical shortcoming. As generally authorised and Schedule 1 water use (RSA, 1998a) is not licensable, yet collectively can constitute large volumes, verification of groundwater use in the study area is very difficult. For this and other reasons (see Section 5.3), a reconciliation of current groundwater use with availability of supply within the framework of future demand also from SGD, is problematic. Further, the distributed spatial extent of groundwater sources makes their enumeration an arduous task that is best addressed in an EIA.

- A number of aspects related to the geology and hydrogeology interaction at depth in the study area are constrained by limited knowledge. These include (a) the occurrence, hydraulic properties of 'aquifer' formations and quality of deep groundwater (>1 000 m), (b) the presence of potable groundwater at depth, (c) the measure of interconnectivity with the shallow aquifer, and (d) the occurrence and geometry of dolerite at depth. Specialised deep drilling is required to elucidate these aspects in order to carry out appropriate risk/impact assessments.

- There is a poor understanding of the nature of basinal groundwater flow and its properties, geometries and controlling factors in the Karoo Basin (Tóth, 1999). Groundwater flow systems serve to transport and distribute the products of water and soil/rock interaction within the basinal domain. Gravity-driven (unconfined and typically shallow) flow systems are relatively 'simple' compared to pressure-driven (confined) flow systems such as most probably characterise the deeper portions of the Karoo Basin. Whereas numerical modelling has been applied successfully in local shallow aquifer environments to resolve and inform groundwater resource behaviour and response, this has not been attempted at a regional or basinal scale. It is therefore presently not possible to comprehend the basinal flow dynamics within the Karoo Basin, and specifically in the study area, beyond a qualitative conceptual model.

- An understanding of the response of the Whitehill Formation and overlying strata to fracking remains poorly understood. For example, to what extent will overlying dolerite sills mitigate against the upward progression of fractures? For example, CIMERA-KARIN borehole KWV-01 intersected a ~18 m thick dolerite sill immediately overlying the Whitehill Formation, and an even thicker ~150 m dolerite sill in the 110 m shallower depth interval 2 037 to 2 186 m below surface.

- In common with most SGD projects globally, knowledge of the background (baseline or reference) groundwater quality is extremely sparse. This is true for the shallow, intermediate and deep environments. As the shallow environment supports a primary water supply function that is particularly vulnerable and at risk, a concerted effort is needed to 'fingerprint' shallow groundwater quality across the study area as completely as possible prior to up-scaled SGD at the latest.

- Improved understanding of the hydrodynamics that describe the interaction of surface water and groundwater is required in order to inform recommendations as to reasonable and responsible setbacks of wells and other activities from surface and groundwater resources, to reduce risks to these critically important resources. This understanding can be gleaned from numerical simulations that would need to be applied at a local scale. The veracity of the outputs would be constrained by the relevance of the conceptual model formulation and input data which, in most instances, are inadequate.

- The inter-dependence that exists between hydrology and the ecology of temporary surface water systems is similarly poorly understood. This interface is not yet served by suitable and appropriate hydrological models to simulate the hydrodynamics of temporary rivers. Even if such models did exist, their application would be constrained by the lack of detailed information and data associated with the often very short-term (hours and days) occurrence of these events, and the equally short-term response of the interconnected hydrosystem. It is therefore difficult to fully comprehend and predict the impact that SGD could have on these systems.

- The effect that additional groundwater extraction for SGD might have on the sustainability of temporary to ephemeral rivers and wetlands in the area is unknown and of great concern. It is possible that over-abstraction could damage these GDE's beyond repair. An added uncertainty is that recharge data area only available for localised areas, but is lacking on a regional scale. Recharge is influenced by land use changes and it is expected that the study area, because of its arid nature, will be very sensitive to a change in land use. A change in land use from natural to agriculture/industrial could result in more pronounced erosion, sedimentation, floods, less infiltration from precipitation and higher rates of evapotranspiration. This uncertainty is aggravated by the limited rainfall and poor/limited distribution of gauging stations in the study area.

- The technological advancement in drilling techniques and well construction practices in the field of SGD, and in particular the field of fracking, is unparalleled in the drilling industry. This extends to the monitoring of the integrity of production wells (see for example Addendum D of EPA, 2015). The closest that the local groundwater fraternity can manage, is the supervision of the drilling and construction of water production boreholes in highly leached and cavernous dolomitic strata (e.g. of the Malmani Subgroup) and highly fractured quartzitic sandstones (e.g. of the Table Mountain Group), often at depths >200 m below surface. Even in these instances, there are few groundwater scientists and technicians who can claim experience and competence in this field. The extent to which this competence will need to be grown depends on the scale of SGD activities. A failure to achieve this will seriously compromise any efforts to exercise regulatory oversight and control over the upstream developmental components of a shale gas industry.

- The volume of waste water (flowback and produced water) that will be generated during full-scale SGD is similarly subject to substantial uncertainty. This also applies to the quality of the waste water produced. These factors limit an appraisal of proper waste water management planning required to protect water resources from contamination.

- One of the greater uncertainties relates to the long-term impacts of SGD on the water resources of the Karoo. These impacts will form part of the legacy of impacts left behind by a defunct shale gas industry in the form of 'abandoned' gas exploration/production wells, and will likely be manifested for decades (or longer) beyond the cessation of SGD. The magnitude and extent of possible long-term contamination of freshwater resources can therefore not be predicted at this stage, as this would require a much better understanding of the complex hydrosystems that characterise the Karoo environment.

- The risk posed by SGD activities to downstream dependent systems including urban and agricultural users as well as environmental resources such as important estuaries is poorly understood and inadequately quantified.

- Finally, it is necessary that the DWS develops its own regulations to govern the exploration and development of petroleum resources as soon as possible. This authority is also best placed to initiate the much needed water resources baseline studies required prior to SGD. Care needs to be taken to ensure that the regulatory process is harmonised between the different authorities that have jurisdiction over the numerous and varied aspects involved.

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5.11 Digital Addenda 5A – 5F

SEPARATE DIGITAL DOCUMENT

Addendum 5A	Presentation of supplementary hydrological data used for the Karoo Shale Gas scientific assessment
Addendum 5B	Sections 88 and 122 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002)
Addendum 5C	Substances that have been detected in flowback water but not in drilling or fracking fluids, and therefore assumed to be derived from underlying substrates
Addendum 5D	Definition Of Buffer/Setback Zones for Dykes and Thermal Springs
Addendum 5E	Figures showing application of setbacks to protect surface- and groundwater resources
Addendum 5F	Monitoring frameworks